The UNITY Formalism

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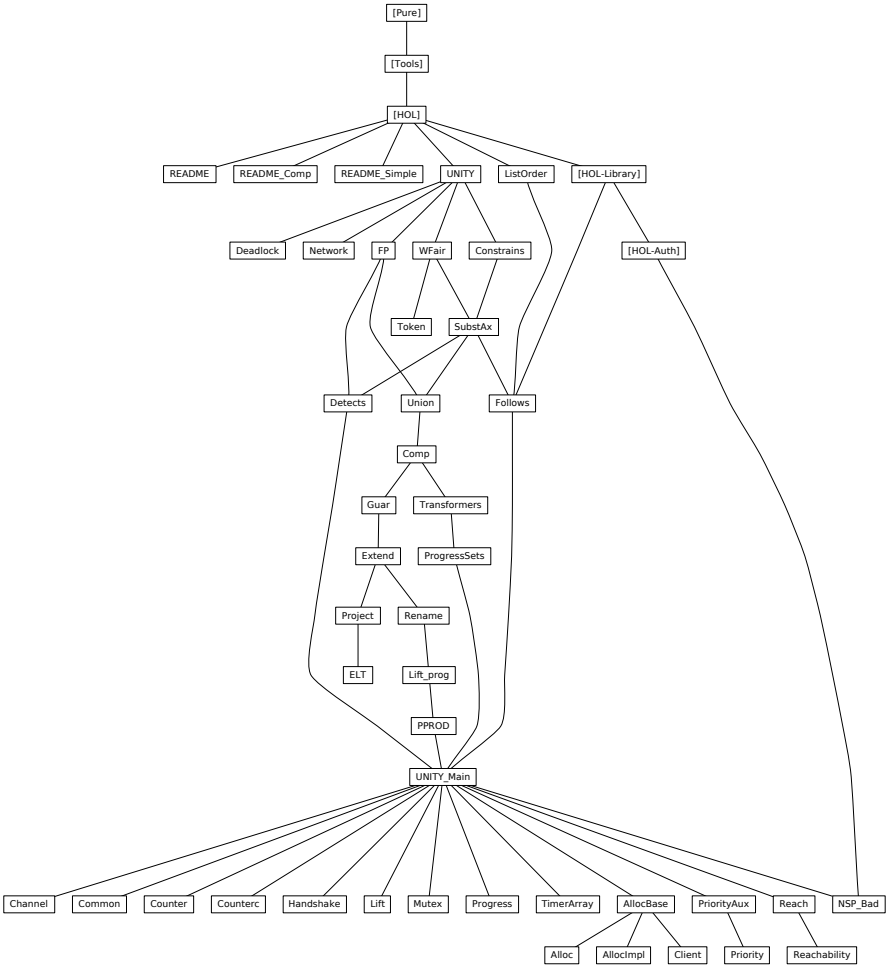
Contents


[Pure]
[Tools]
[HOL]
README
README_Comp
README_Simple
UNITY
ListOrder
[HOL-Library]
Deadlock
Network
FP
WFair
Constrains
[HOL-Auth]
Token
SubstAx
Detects
Union
Follows
Comp
Guar
Transformers
Extend
ProgressSets
Project
Rename
ELT
Lift_prog
PPROD
UNITY_Main
Channel
Common
Counter
Counterc
Handshake
Lift
Mutex
Progress
TimerArray
AllocBase
PriorityAux
Reach
NSP_Bad
Alloc
AllocImpl
Client
Priority
Reachability

1 The Basic UNITY Theory

theory *UNITY* **imports** *Main* **begin**

definition
  "Program =
    *{(init:: 'a set, acts :: ('a * 'a)set set,*
      *allowed :: ('a * 'a)set set). Id ∈ acts & Id ∈ allowed}"*

typedef *'a program = "Program :: ('a set * ('a * 'a) set set * ('a * 'a) set set) set"*
  morphisms *Rep_Program Abs_Program*
  unfolding *Program_def* **by** *blast*

definition *Acts :: "'a program => ('a * 'a)set set"* **where**
    "Acts F == (%(init, acts, allowed). acts) (Rep_Program F)"

definition *"constrains" :: "['a set, 'a set] => 'a program set"* (**infixl** *"co" 60)* **where**
    "A co B == {F. ∀act ∈ Acts F. act``A ⊆ B}"

definition *unless :: "['a set, 'a set] => 'a program set"* (**infixl** *"unless" 60)* **where**
    "A unless B == (A-B) co (A ∪ B)"

definition *mk_program :: "('a set * ('a * 'a)set set * ('a * 'a)set set)*
                  => 'a program" **where**
    "mk_program == %(init, acts, allowed).
                      Abs_Program (init, insert Id acts, insert Id allowed)"

definition *Init :: "'a program => 'a set"* **where**
    "Init F == (%(init, acts, allowed). init) (Rep_Program F)"

definition *AllowedActs :: "'a program => ('a * 'a)set set"* **where**
    "AllowedActs F == (%(init, acts, allowed). allowed) (Rep_Program F)"

definition *Allowed :: "'a program => 'a program set"* **where**
    "Allowed F == {G. Acts G ⊆ AllowedActs F}"

definition *stable :: "'a set => 'a program set"* **where**
    "stable A == A co A"

definition *strongest_rhs :: "['a program, 'a set] => 'a set"* **where**
    "strongest_rhs F A == ⋂{B. F ∈ A co B}"

definition *invariant :: "'a set => 'a program set"* **where**
    "invariant A == {F. Init F ⊆ A} ∩ stable A"

definition *increasing :: "['a => 'b::{order}] => 'a program set"* **where**
    — Polymorphic in both states and the meaning of $\leq$
    "increasing f == ⋂z. stable {s. z ≤ f s}"

1.0.1 The abstract type of programs

lemmas *program_typedef =*
Rep_Program Rep_Program_inverse Abs_Program_inverse
Program_def Init_def Acts_def AllowedActs_def mk_program_def

lemma *Id_in_Acts [iff]: "Id ∈ Acts F"*
apply *(cut_tac x = F* **in** *Rep_Program)*
apply *(auto simp add: program_typedef)*
done

lemma *insert_Id_Acts [iff]: "insert Id (Acts F) = Acts F"*
by *(simp add: insert_absorb)*

lemma *Acts_nonempty [simp]: "Acts F ≠ {}"*
by *auto*

lemma *Id_in_AllowedActs [iff]: "Id ∈ AllowedActs F"*
apply *(cut_tac x = F* **in** *Rep_Program)*
apply *(auto simp add: program_typedef)*
done

lemma *insert_Id_AllowedActs [iff]: "insert Id (AllowedActs F) = AllowedActs F"*
by *(simp add: insert_absorb)*

1.0.2 Inspectors for type "program"

lemma *Init_eq [simp]: "Init (mk_program (init,acts,allowed)) = init"*
by *(simp add: program_typedef)*

lemma *Acts_eq [simp]: "Acts (mk_program (init,acts,allowed)) = insert Id acts"*
by *(simp add: program_typedef)*

lemma *AllowedActs_eq [simp]:*
"AllowedActs (mk_program (init,acts,allowed)) = insert Id allowed"
by *(simp add: program_typedef)*

1.0.3 Equality for UNITY programs

lemma *surjective_mk_program [simp]:*
"mk_program (Init F, Acts F, AllowedActs F) = F"
apply *(cut_tac x = F* **in** *Rep_Program)*
apply *(auto simp add: program_typedef)*
apply *(drule_tac f = Abs_Program* **in** *arg_cong)+*
apply *(simp add: program_typedef insert_absorb)*
done

lemma *program_equalityI:*
"[| Init F = Init G; Acts F = Acts G; AllowedActs F = AllowedActs G |]

==> F = G"
apply *(rule_tac t = F* **in** *surjective_mk_program [THEN subst])*
apply *(rule_tac t = G* **in** *surjective_mk_program [THEN subst], simp)*

done

lemma *program_equalityE:*
```
     "[| F = G;
         [| Init F = Init G; Acts F = Acts G; AllowedActs F = AllowedActs G
|]
         ==> P |] ==> P"
```
by *simp*

lemma *program_equality_iff:*
```
     "(F=G) =
      (Init F = Init G & Acts F = Acts G &AllowedActs F = AllowedActs G)"
```
by *(blast intro: program_equalityI program_equalityE)*

1.0.4 co

lemma *constrainsI:*
```
    "(!!act s s'. [| act ∈ Acts F;  (s,s') ∈ act;  s ∈ A |] ==> s' ∈ A')

     ==> F ∈ A co A'"
```
by *(simp add: constrains_def, blast)*

lemma *constrainsD:*
```
    "[| F ∈ A co A'; act ∈ Acts F;  (s,s') ∈ act;  s ∈ A |] ==> s' ∈ A'"
```
by *(unfold constrains_def, blast)*

lemma *constrains_empty [iff]: "F ∈ {} co B"*
by *(unfold constrains_def, blast)*

lemma *constrains_empty2 [iff]: "(F ∈ A co {}) = (A={})"*
by *(unfold constrains_def, blast)*

lemma *constrains_UNIV [iff]: "(F ∈ UNIV co B) = (B = UNIV)"*
by *(unfold constrains_def, blast)*

lemma *constrains_UNIV2 [iff]: "F ∈ A co UNIV"*
by *(unfold constrains_def, blast)*

monotonic in 2nd argument

lemma *constrains_weaken_R:*
```
    "[| F ∈ A co A'; A'<=B' |] ==> F ∈ A co B'"
```
by *(unfold constrains_def, blast)*

anti-monotonic in 1st argument

lemma *constrains_weaken_L:*
```
    "[| F ∈ A co A'; B ⊆ A |] ==> F ∈ B co A'"
```
by *(unfold constrains_def, blast)*

lemma *constrains_weaken:*
```
   "[| F ∈ A co A'; B ⊆ A; A'<=B' |] ==> F ∈ B co B'"
```
by *(unfold constrains_def, blast)*

1.0.5 Union

lemma *constrains_Un:*

```
    "[| F ∈ A co A'; F ∈ B co B' |] ==> F ∈ (A ∪ B) co (A' ∪ B')"
by (unfold constrains_def, blast)

lemma constrains_UN:
    "(!!i. i ∈ I ==> F ∈ (A i) co (A' i))
     ==> F ∈ (⋃i ∈ I. A i) co (⋃i ∈ I. A' i)"
by (unfold constrains_def, blast)

lemma constrains_Un_distrib: "(A ∪ B) co C = (A co C) ∩ (B co C)"
by (unfold constrains_def, blast)

lemma constrains_UN_distrib: "(⋃i ∈ I. A i) co B = (⋂i ∈ I. A i co B)"
by (unfold constrains_def, blast)

lemma constrains_Int_distrib: "C co (A ∩ B) = (C co A) ∩ (C co B)"
by (unfold constrains_def, blast)

lemma constrains_INT_distrib: "A co (⋂i ∈ I. B i) = (⋂i ∈ I. A co B i)"
by (unfold constrains_def, blast)
```

1.0.6 Intersection

```
lemma constrains_Int:
    "[| F ∈ A co A'; F ∈ B co B' |] ==> F ∈ (A ∩ B) co (A' ∩ B')"
by (unfold constrains_def, blast)

lemma constrains_INT:
    "(!!i. i ∈ I ==> F ∈ (A i) co (A' i))
     ==> F ∈ (⋂i ∈ I. A i) co (⋂i ∈ I. A' i)"
by (unfold constrains_def, blast)

lemma constrains_imp_subset: "F ∈ A co A' ==> A ⊆ A'"
by (unfold constrains_def, auto)
```

The reasoning is by subsets since "co" refers to single actions only. So this rule isn't that useful.

```
lemma constrains_trans:
    "[| F ∈ A co B; F ∈ B co C |] ==> F ∈ A co C"
by (unfold constrains_def, blast)

lemma constrains_cancel:
   "[| F ∈ A co (A' ∪ B); F ∈ B co B' |] ==> F ∈ A co (A' ∪ B')"
by (unfold constrains_def, clarify, blast)
```

1.0.7 unless

```
lemma unlessI: "F ∈ (A-B) co (A ∪ B) ==> F ∈ A unless B"
by (unfold unless_def, assumption)

lemma unlessD: "F ∈ A unless B ==> F ∈ (A-B) co (A ∪ B)"
by (unfold unless_def, assumption)
```

1.0.8 stable

```
lemma stableI: "F ∈ A co A ==> F ∈ stable A"
```

by *(unfold stable_def, assumption)*

lemma *stableD: "F ∈ stable A ==> F ∈ A co A"*
by *(unfold stable_def, assumption)*

lemma *stable_UNIV [simp]: "stable UNIV = UNIV"*
by *(unfold stable_def constrains_def, auto)*

1.0.9 Union

lemma *stable_Un:*
"[| F ∈ stable A; F ∈ stable A' |] ==> F ∈ stable (A ∪ A')"

apply *(unfold stable_def)*
apply *(blast intro: constrains_Un)*
done

lemma *stable_UN:*
"(!!i. i ∈ I ==> F ∈ stable (A i)) ==> F ∈ stable (⋃i ∈ I. A i)"
apply *(unfold stable_def)*
apply *(blast intro: constrains_UN)*
done

lemma *stable_Union:*
"(!!A. A ∈ X ==> F ∈ stable A) ==> F ∈ stable (⋃X)"
by *(unfold stable_def constrains_def, blast)*

1.0.10 Intersection

lemma *stable_Int:*
"[| F ∈ stable A; F ∈ stable A' |] ==> F ∈ stable (A ∩ A')"
apply *(unfold stable_def)*
apply *(blast intro: constrains_Int)*
done

lemma *stable_INT:*
"(!!i. i ∈ I ==> F ∈ stable (A i)) ==> F ∈ stable (⋂i ∈ I. A i)"
apply *(unfold stable_def)*
apply *(blast intro: constrains_INT)*
done

lemma *stable_Inter:*
"(!!A. A ∈ X ==> F ∈ stable A) ==> F ∈ stable (⋂X)"
by *(unfold stable_def constrains_def, blast)*

lemma *stable_constrains_Un:*
"[| F ∈ stable C; F ∈ A co (C ∪ A') |] ==> F ∈ (C ∪ A) co (C ∪ A')"
by *(unfold stable_def constrains_def, blast)*

lemma *stable_constrains_Int:*
"[| F ∈ stable C; F ∈ (C ∩ A) co A' |] ==> F ∈ (C ∩ A) co (C ∩ A')"
by *(unfold stable_def constrains_def, blast)*

lemmas *stable_constrains_stable = stable_constrains_Int[THEN stableI]*

1.0.11 invariant

lemma *invariantI: "[| Init F ⊆ A; F ∈ stable A |] ==> F ∈ invariant A"*
by *(simp add: invariant_def)*

Could also say *invariant A ∩ invariant B ⊆ invariant (A ∩ B)*

lemma *invariant_Int:*
"[| F ∈ invariant A; F ∈ invariant B |] ==> F ∈ invariant (A ∩ B)"
by *(auto simp add: invariant_def stable_Int)*

1.0.12 increasing

lemma *increasingD:*
"F ∈ increasing f ==> F ∈ stable {s. z ⊆ f s}"
by *(unfold increasing_def, blast)*

lemma *increasing_constant [iff]: "F ∈ increasing (%s. c)"*
by *(unfold increasing_def stable_def, auto)*

lemma *mono_increasing_o:*
"mono g ==> increasing f ⊆ increasing (g o f)"
apply *(unfold increasing_def stable_def constrains_def, auto)*
apply *(blast intro: monoD order_trans)*
done

lemma *strict_increasingD:*
"!!z::nat. F ∈ increasing f ==> F ∈ stable {s. z < f s}"
by *(simp add: increasing_def Suc_le_eq [symmetric])*

lemma *elimination:*
"[| ∀m ∈ M. F ∈ {s. s x = m} co (B m) |]
==> F ∈ {s. s x ∈ M} co (⋃m ∈ M. B m)"
by *(unfold constrains_def, blast)*

As above, but for the trivial case of a one-variable state, in which the state is identified with its one variable.

lemma *elimination_sing:*
"(∀m ∈ M. F ∈ {m} co (B m)) ==> F ∈ M co (⋃m ∈ M. B m)"
by *(unfold constrains_def, blast)*

1.0.13 Theoretical Results from Section 6

lemma *constrains_strongest_rhs:*
"F ∈ A co (strongest_rhs F A)"
by *(unfold constrains_def strongest_rhs_def, blast)*

lemma *strongest_rhs_is_strongest:*
"F ∈ A co B ==> strongest_rhs F A ⊆ B"
by *(unfold constrains_def strongest_rhs_def, blast)*

1.0.14 Ad-hoc set-theory rules

lemma *Un_Diff_Diff [simp]: "A ∪ B - (A - B) = B"*
by *blast*

lemma *Int_Union_Union: "⋃B ∩ A = ⋃((%C. C ∩ A)‘B)"*
by *blast*

Needed for WF reasoning in WFair.thy

lemma *Image_less_than [simp]: "less_than `` {k} = greaterThan k"*
by *blast*

lemma *Image_inverse_less_than [simp]: "less_than^{-1} `` {k} = lessThan k"*
by *blast*

1.1 Partial versus Total Transitions

definition *totalize_act :: "('a * 'a)set => ('a * 'a)set"* **where**
"totalize_act act == act ∪ Id_on (-(Domain act))"

definition *totalize :: "'a program => 'a program"* **where**
"totalize F == mk_program (Init F,
totalize_act ‘ Acts F,
AllowedActs F)"

definition *mk_total_program :: "('a set * ('a * 'a)set set * ('a * 'a)set set)*
=> 'a program" **where**
"mk_total_program args == totalize (mk_program args)"

definition *all_total :: "'a program => bool"* **where**
"all_total F == ∀act ∈ Acts F. Domain act = UNIV"

lemma *insert_Id_image_Acts: "f Id = Id ==> insert Id (f‘Acts F) = f ‘ Acts F"*
by *(blast intro: sym [THEN image_eqI])*

1.1.1 Basic properties

lemma *totalize_act_Id [simp]: "totalize_act Id = Id"*
by *(simp add: totalize_act_def)*

lemma *Domain_totalize_act [simp]: "Domain (totalize_act act) = UNIV"*
by *(auto simp add: totalize_act_def)*

lemma *Init_totalize [simp]: "Init (totalize F) = Init F"*
by *(unfold totalize_def, auto)*

lemma *Acts_totalize [simp]: "Acts (totalize F) = (totalize_act ‘ Acts F)"*
by *(simp add: totalize_def insert_Id_image_Acts)*

lemma *AllowedActs_totalize [simp]: "AllowedActs (totalize F) = AllowedActs F"*
by *(simp add: totalize_def)*

```
lemma totalize_constrains_iff [simp]: "(totalize F ∈ A co B) = (F ∈ A co
B)"
by (simp add: totalize_def totalize_act_def constrains_def, blast)

lemma totalize_stable_iff [simp]: "(totalize F ∈ stable A) = (F ∈ stable
A)"
by (simp add: stable_def)

lemma totalize_invariant_iff [simp]:
     "(totalize F ∈ invariant A) = (F ∈ invariant A)"
by (simp add: invariant_def)

lemma all_total_totalize: "all_total (totalize F)"
by (simp add: totalize_def all_total_def)

lemma Domain_iff_totalize_act: "(Domain act = UNIV) = (totalize_act act =
act)"
by (force simp add: totalize_act_def)

lemma all_total_imp_totalize: "all_total F ==> (totalize F = F)"
apply (simp add: all_total_def totalize_def)
apply (rule program_equalityI)
  apply (simp_all add: Domain_iff_totalize_act image_def)
done

lemma all_total_iff_totalize: "all_total F = (totalize F = F)"
apply (rule iffI)
 apply (erule all_total_imp_totalize)
apply (erule subst)
apply (rule all_total_totalize)
done

lemma mk_total_program_constrains_iff [simp]:
     "(mk_total_program args ∈ A co B) = (mk_program args ∈ A co B)"
by (simp add: mk_total_program_def)
```

1.2 Rules for Lazy Definition Expansion

They avoid expanding the full program, which is a large expression

```
lemma def_prg_Init:
     "F = mk_total_program (init,acts,allowed) ==> Init F = init"
by (simp add: mk_total_program_def)

lemma def_prg_Acts:
     "F = mk_total_program (init,acts,allowed)
      ==> Acts F = insert Id (totalize_act ‘ acts)"
by (simp add: mk_total_program_def)

lemma def_prg_AllowedActs:
     "F = mk_total_program (init,acts,allowed)
      ==> AllowedActs F = insert Id allowed"
by (simp add: mk_total_program_def)
```

An action is expanded if a pair of states is being tested against it

lemma *def_act_simp:*
"act = {(s,s'). P s s'} ==> ((s,s') ∈ act) = P s s'"
by *(simp add: mk_total_program_def)*

A set is expanded only if an element is being tested against it

lemma *def_set_simp: "A = B ==> (x ∈ A) = (x ∈ B)"*
by *(simp add: mk_total_program_def)*

1.2.1 Inspectors for type "program"

lemma *Init_total_eq [simp]:*
"Init (mk_total_program (init,acts,allowed)) = init"
by *(simp add: mk_total_program_def)*

lemma *Acts_total_eq [simp]:*
"Acts(mk_total_program(init,acts,allowed)) = insert Id (totalize_act`acts)"
by *(simp add: mk_total_program_def)*

lemma *AllowedActs_total_eq [simp]:*
"AllowedActs (mk_total_program (init,acts,allowed)) = insert Id allowed"
by *(auto simp add: mk_total_program_def)*

end

2 Fixed Point of a Program

theory *FP* **imports** *UNITY* **begin**

definition *FP_Orig :: "'a program => 'a set"* **where**
"FP_Orig F == ⋃{A. ∀B. F ∈ stable (A ∩ B)}"

definition *FP :: "'a program => 'a set"* **where**
"FP F == {s. F ∈ stable {s}}"

lemma *stable_FP_Orig_Int: "F ∈ stable (FP_Orig F Int B)"*
apply *(simp only: FP_Orig_def stable_def Int_Union2)*
apply *(blast intro: constrains_UN)*
done

lemma *FP_Orig_weakest:*
"(⋀B. F ∈ stable (A ∩ B)) ⟹ A <= FP_Orig F"
by *(simp add: FP_Orig_def stable_def, blast)*

lemma *stable_FP_Int: "F ∈ stable (FP F ∩ B)"*
proof -
have *"F ∈ stable (⋃x∈B. FP F ∩ {x})"*
apply *(simp only: Int_insert_right FP_def stable_def)*
apply *(rule constrains_UN)*
apply *simp*
done
also have *"(⋃x∈B. FP F ∩ {x}) = FP F ∩ B"*
by *simp*
finally show *?thesis* .

qed

lemma *FP_equivalence: "FP F = FP_Orig F"*
apply *(rule equalityI)*
apply *(rule stable_FP_Int [THEN FP_Orig_weakest])*
apply *(simp add: FP_Orig_def FP_def, clarify)*
apply *(drule_tac x = "{x}"* **in** *spec)*
apply *(simp add: Int_insert_right)*
done

lemma *FP_weakest:*
"(⋀B. F ∈ stable (A Int B)) ⟹ A <= FP F"
by *(simp add: FP_equivalence FP_Orig_weakest)*

lemma *Compl_FP:*
"-(FP F) = (UN act: Acts F. -{s. act``{s} <= {s}})"
by *(simp add: FP_def stable_def constrains_def, blast)*

lemma *Diff_FP: "A - (FP F) = (UN act: Acts F. A - {s. act``{s} <= {s}})"*
by *(simp add: Diff_eq Compl_FP)*

lemma *totalize_FP [simp]: "FP (totalize F) = FP F"*
by *(simp add: FP_def)*

end

3 Progress

theory *WFair* **imports** *UNITY* **begin**

The original version of this theory was based on weak fairness. (Thus, the entire UNITY development embodied this assumption, until February 2003.) Weak fairness states that if a command is enabled continuously, then it is eventually executed. Ernie Cohen suggested that I instead adopt unconditional fairness: every command is executed infinitely often.

In fact, Misra's paper on "Progress" seems to be ambiguous about the correct interpretation, and says that the two forms of fairness are equivalent. They differ only on their treatment of partial transitions, which under unconditional fairness behave magically. That is because if there are partial transitions then there may be no fair executions, making all leads-to properties hold vacuously.

Unconditional fairness has some great advantages. By distinguishing partial transitions from total ones that are the identity on part of their domain, it is more expressive. Also, by simplifying the definition of the transient property, it simplifies many proofs. A drawback is that some laws only hold under the assumption that all transitions are total. The best-known of these is the impossibility law for leads-to.

definition

— This definition specifies conditional fairness. The rest of the theory is generic to all forms of fairness. To get weak fairness, conjoin the inclusion below with `A ⊆ Domain act`, which specifies that the action is enabled over all of `A`.

```
  transient :: "'a set => 'a program set" where
    "transient A == {F. ∃act∈Acts F. act``A ⊆ -A}"

definition
  ensures :: "['a set, 'a set] => 'a program set"       (infixl "ensures" 60)
where
    "A ensures B == (A-B co A ∪ B) ∩ transient (A-B)"


inductive_set
  leads :: "'a program => ('a set * 'a set) set"
    — LEADS-TO constant for the inductive definition
  for F :: "'a program"
  where

    Basis:  "F ∈ A ensures B ==> (A,B) ∈ leads F"

  | Trans:  "[| (A,B) ∈ leads F;  (B,C) ∈ leads F |] ==> (A,C) ∈ leads F"

  | Union:  "∀A ∈ S. (A,B) ∈ leads F ==> (Union S, B) ∈ leads F"


definition leadsTo :: "['a set, 'a set] => 'a program set" (infixl "leadsTo"
60) where
     — visible version of the LEADS-TO relation
    "A leadsTo B == {F. (A,B) ∈ leads F}"

definition wlt :: "['a program, 'a set] => 'a set" where
     — predicate transformer: the largest set that leads to B
    "wlt F B == ⋃{A. F ∈ A leadsTo B}"

notation leadsTo  (infixl "↦" 60)
```

3.1 transient

```
lemma stable_transient:
    "[| F ∈ stable A; F ∈ transient A |] ==> ∃act∈Acts F. A ⊆ - (Domain
act)"
apply (simp add: stable_def constrains_def transient_def, clarify)
apply (rule rev_bexI, auto)
done

lemma stable_transient_empty:
    "[| F ∈ stable A; F ∈ transient A; all_total F |] ==> A = {}"
apply (drule stable_transient, assumption)
apply (simp add: all_total_def)
done

lemma transient_strengthen:
    "[| F ∈ transient A; B ⊆ A |] ==> F ∈ transient B"
apply (unfold transient_def, clarify)
apply (blast intro!: rev_bexI)
done
```

```
lemma transientI:
    "[| act ∈ Acts F;  act``A ⊆ -A |] ==> F ∈ transient A"
by (unfold transient_def, blast)

lemma transientE:
    "[| F ∈ transient A;
        ⋀act. [| act ∈ Acts F;  act``A ⊆ -A |] ==> P |]
     ==> P"
by (unfold transient_def, blast)

lemma transient_empty [simp]: "transient {} = UNIV"
by (unfold transient_def, auto)
```

This equation recovers the notion of weak fairness. A totalized program satisfies a transient assertion just if the original program contains a suitable action that is also enabled.

```
lemma totalize_transient_iff:
   "(totalize F ∈ transient A) = (∃act∈Acts F. A ⊆ Domain act & act``A ⊆
-A)"
apply (simp add: totalize_def totalize_act_def transient_def
                 Un_Image, safe)
apply (blast intro!: rev_bexI)+
done

lemma totalize_transientI:
    "[| act ∈ Acts F;  A ⊆ Domain act;  act``A ⊆ -A |]
     ==> totalize F ∈ transient A"
by (simp add: totalize_transient_iff, blast)
```

3.2 ensures

```
lemma ensuresI:
    "[| F ∈ (A-B) co (A ∪ B); F ∈ transient (A-B) |] ==> F ∈ A ensures B"
by (unfold ensures_def, blast)

lemma ensuresD:
    "F ∈ A ensures B ==> F ∈ (A-B) co (A ∪ B) & F ∈ transient (A-B)"
by (unfold ensures_def, blast)

lemma ensures_weaken_R:
    "[| F ∈ A ensures A'; A'<=B' |] ==> F ∈ A ensures B'"
apply (unfold ensures_def)
apply (blast intro: constrains_weaken transient_strengthen)
done
```

The L-version (precondition strengthening) fails, but we have this

```
lemma stable_ensures_Int:
    "[| F ∈ stable C;  F ∈ A ensures B |]
    ==> F ∈ (C ∩ A) ensures (C ∩ B)"
apply (unfold ensures_def)
apply (auto simp add: ensures_def Int_Un_distrib [symmetric] Diff_Int_distrib
[symmetric])
prefer 2 apply (blast intro: transient_strengthen)
```

```
apply (blast intro: stable_constrains_Int constrains_weaken)
done

lemma stable_transient_ensures:
     "[| F ∈ stable A;  F ∈ transient C;  A ⊆ B ∪ C |] ==> F ∈ A ensures
B"
apply (simp add: ensures_def stable_def)
apply (blast intro: constrains_weaken transient_strengthen)
done

lemma ensures_eq: "(A ensures B) = (A unless B) ∩ transient (A-B)"
by (simp (no_asm) add: ensures_def unless_def)
```

3.3 leadsTo

```
lemma leadsTo_Basis [intro]: "F ∈ A ensures B ==> F ∈ A leadsTo B"
apply (unfold leadsTo_def)
apply (blast intro: leads.Basis)
done

lemma leadsTo_Trans:
     "[| F ∈ A leadsTo B;  F ∈ B leadsTo C |] ==> F ∈ A leadsTo C"
apply (unfold leadsTo_def)
apply (blast intro: leads.Trans)
done

lemma leadsTo_Basis':
     "[| F ∈ A co A ∪ B; F ∈ transient A |] ==> F ∈ A leadsTo B"
apply (drule_tac B = "A-B" in constrains_weaken_L)
apply (drule_tac [2] B = "A-B" in transient_strengthen)
apply (rule_tac [3] ensuresI [THEN leadsTo_Basis])
apply (blast+)
done

lemma transient_imp_leadsTo: "F ∈ transient A ==> F ∈ A leadsTo (-A)"
by (simp (no_asm_simp) add: leadsTo_Basis ensuresI Compl_partition)
```

Useful with cancellation, disjunction

```
lemma leadsTo_Un_duplicate: "F ∈ A leadsTo (A' ∪ A') ==> F ∈ A leadsTo A'"
by (simp add: Un_ac)

lemma leadsTo_Un_duplicate2:
     "F ∈ A leadsTo (A' ∪ C ∪ C) ==> F ∈ A leadsTo (A' ∪ C)"
by (simp add: Un_ac)
```

The Union introduction rule as we should have liked to state it

```
lemma leadsTo_Union:
    "(!!A. A ∈ S ==> F ∈ A leadsTo B) ==> F ∈ (⋃S) leadsTo B"
apply (unfold leadsTo_def)
apply (blast intro: leads.Union)
done

lemma leadsTo_Union_Int:
 "(!!A. A ∈ S ==> F ∈ (A ∩ C) leadsTo B) ==> F ∈ (⋃S ∩ C) leadsTo B"
```

```
apply (unfold leadsTo_def)
apply (simp only: Int_Union_Union)
apply (blast intro: leads.Union)
done

lemma leadsTo_UN:
    "(!!i. i ∈ I ==> F ∈ (A i) leadsTo B) ==> F ∈ (⋃i ∈ I. A i) leadsTo
B"
apply (blast intro: leadsTo_Union)
done
```

Binary union introduction rule

```
lemma leadsTo_Un:
     "[| F ∈ A leadsTo C; F ∈ B leadsTo C |] ==> F ∈ (A ∪ B) leadsTo C"
  using leadsTo_Union [of "{A, B}" F C] by auto

lemma single_leadsTo_I:
     "(!!x. x ∈ A ==> F ∈ {x} leadsTo B) ==> F ∈ A leadsTo B"
by (subst UN_singleton [symmetric], rule leadsTo_UN, blast)
```

The INDUCTION rule as we should have liked to state it

```
lemma leadsTo_induct:
  "[| F ∈ za leadsTo zb;
      !!A B. F ∈ A ensures B ==> P A B;
      !!A B C. [| F ∈ A leadsTo B; P A B; F ∈ B leadsTo C; P B C |]
               ==> P A C;
      !!B S. ∀A ∈ S. F ∈ A leadsTo B & P A B ==> P (⋃S) B
   |] ==> P za zb"
apply (unfold leadsTo_def)
apply (drule CollectD, erule leads.induct)
apply (blast+)
done


lemma subset_imp_ensures: "A ⊆ B ==> F ∈ A ensures B"
by (unfold ensures_def constrains_def transient_def, blast)

lemmas subset_imp_leadsTo = subset_imp_ensures [THEN leadsTo_Basis]

lemmas leadsTo_refl = subset_refl [THEN subset_imp_leadsTo]

lemmas empty_leadsTo = empty_subsetI [THEN subset_imp_leadsTo, simp]

lemmas leadsTo_UNIV = subset_UNIV [THEN subset_imp_leadsTo, simp]
```

Lemma is the weak version: can't see how to do it in one step

```
lemma leadsTo_induct_pre_lemma:
  "[| F ∈ za leadsTo zb;
      P zb;
      !!A B. [| F ∈ A ensures B;  P B |] ==> P A;
      !!S. ∀A ∈ S. P A ==> P (⋃S)
   |] ==> P za"
```

by induction on this formula

apply *(subgoal_tac "P zb --> P za")*

now solve first subgoal: this formula is sufficient

apply *(blast intro: leadsTo_refl)*
apply *(erule leadsTo_induct)*
apply *(blast+)*
done

lemma *leadsTo_induct_pre:*
"[| F ∈ za leadsTo zb;
P zb;
!!A B. [| F ∈ A ensures B; F ∈ B leadsTo zb; P B |] ==> P A;
!!S. ∀A ∈ S. F ∈ A leadsTo zb & P A ==> P (⋃S)
|] ==> P za"
apply *(subgoal_tac "F ∈ za leadsTo zb & P za")*
apply *(erule conjunct2)*
apply *(erule leadsTo_induct_pre_lemma)*
prefer *3* **apply** *(blast intro: leadsTo_Union)*
prefer *2* **apply** *(blast intro: leadsTo_Trans)*
apply *(blast intro: leadsTo_refl)*
done

lemma *leadsTo_weaken_R: "[| F ∈ A leadsTo A'; A'<=B' |] ==> F ∈ A leadsTo B'"*
by *(blast intro: subset_imp_leadsTo leadsTo_Trans)*

lemma *leadsTo_weaken_L:*
"[| F ∈ A leadsTo A'; B ⊆ A |] ==> F ∈ B leadsTo A'"
by *(blast intro: leadsTo_Trans subset_imp_leadsTo)*

Distributes over binary unions

lemma *leadsTo_Un_distrib:*
"F ∈ (A ∪ B) leadsTo C = (F ∈ A leadsTo C & F ∈ B leadsTo C)"
by *(blast intro: leadsTo_Un leadsTo_weaken_L)*

lemma *leadsTo_UN_distrib:*
"F ∈ (⋃i ∈ I. A i) leadsTo B = (∀i ∈ I. F ∈ (A i) leadsTo B)"
by *(blast intro: leadsTo_UN leadsTo_weaken_L)*

lemma *leadsTo_Union_distrib:*
"F ∈ (⋃S) leadsTo B = (∀A ∈ S. F ∈ A leadsTo B)"
by *(blast intro: leadsTo_Union leadsTo_weaken_L)*

lemma *leadsTo_weaken:*
"[| F ∈ A leadsTo A'; B ⊆ A; A'<=B' |] ==> F ∈ B leadsTo B'"
by *(blast intro: leadsTo_weaken_R leadsTo_weaken_L leadsTo_Trans)*

Set difference: maybe combine with *leadsTo_weaken_L*??

lemma *leadsTo_Diff:*
"[| F ∈ (A-B) leadsTo C; F ∈ B leadsTo C |] ==> F ∈ A leadsTo C"
by *(blast intro: leadsTo_Un leadsTo_weaken)*

```
lemma leadsTo_UN_UN:
   "(!! i. i ∈ I ==> F ∈ (A i) leadsTo (A' i))
    ==> F ∈ (⋃i ∈ I. A i) leadsTo (⋃i ∈ I. A' i)"
apply (blast intro: leadsTo_Union leadsTo_weaken_R)
done
```

Binary union version

```
lemma leadsTo_Un_Un:
     "[| F ∈ A leadsTo A'; F ∈ B leadsTo B' |]
      ==> F ∈ (A ∪ B) leadsTo (A' ∪ B')"
by (blast intro: leadsTo_Un leadsTo_weaken_R)
```

```
lemma leadsTo_cancel2:
     "[| F ∈ A leadsTo (A' ∪ B); F ∈ B leadsTo B' |]
      ==> F ∈ A leadsTo (A' ∪ B')"
by (blast intro: leadsTo_Un_Un subset_imp_leadsTo leadsTo_Trans)

lemma leadsTo_cancel_Diff2:
     "[| F ∈ A leadsTo (A' ∪ B); F ∈ (B-A') leadsTo B' |]
      ==> F ∈ A leadsTo (A' ∪ B')"
apply (rule leadsTo_cancel2)
prefer 2 apply assumption
apply (simp_all (no_asm_simp))
done

lemma leadsTo_cancel1:
     "[| F ∈ A leadsTo (B ∪ A'); F ∈ B leadsTo B' |]
    ==> F ∈ A leadsTo (B' ∪ A')"
apply (simp add: Un_commute)
apply (blast intro!: leadsTo_cancel2)
done

lemma leadsTo_cancel_Diff1:
     "[| F ∈ A leadsTo (B ∪ A'); F ∈ (B-A') leadsTo B' |]
    ==> F ∈ A leadsTo (B' ∪ A')"
apply (rule leadsTo_cancel1)
prefer 2 apply assumption
apply (simp_all (no_asm_simp))
done
```

The impossibility law

```
lemma leadsTo_empty: "[|F ∈ A leadsTo {}; all_total F|] ==> A={}"
apply (erule leadsTo_induct_pre)
apply (simp_all add: ensures_def constrains_def transient_def all_total_def,
clarify)
apply (drule bspec, assumption)+
apply blast
done
```

3.4 PSP: Progress-Safety-Progress

Special case of PSP: Misra's "stable conjunction"

```
lemma psp_stable:
   "[| F ∈ A leadsTo A'; F ∈ stable B |]
    ==> F ∈ (A ∩ B) leadsTo (A' ∩ B)"
apply (unfold stable_def)
apply (erule leadsTo_induct)
prefer 3 apply (blast intro: leadsTo_Union_Int)
prefer 2 apply (blast intro: leadsTo_Trans)
apply (rule leadsTo_Basis)
apply (simp add: ensures_def Diff_Int_distrib2 [symmetric] Int_Un_distrib2
[symmetric])
apply (blast intro: transient_strengthen constrains_Int)
done

lemma psp_stable2:
   "[| F ∈ A leadsTo A'; F ∈ stable B |] ==> F ∈ (B ∩ A) leadsTo (B ∩ A')"
by (simp add: psp_stable Int_ac)

lemma psp_ensures:
   "[| F ∈ A ensures A'; F ∈ B co B' |]
    ==> F ∈ (A ∩ B') ensures ((A' ∩ B) ∪ (B' - B))"
apply (unfold ensures_def constrains_def, clarify)
apply (blast intro: transient_strengthen)
done

lemma psp:
     "[| F ∈ A leadsTo A'; F ∈ B co B' |]
      ==> F ∈ (A ∩ B') leadsTo ((A' ∩ B) ∪ (B' - B))"
apply (erule leadsTo_induct)
  prefer 3 apply (blast intro: leadsTo_Union_Int)
```

Basis case

```
 apply (blast intro: psp_ensures)
```

Transitivity case has a delicate argument involving "cancellation"

```
apply (rule leadsTo_Un_duplicate2)
apply (erule leadsTo_cancel_Diff1)
apply (simp add: Int_Diff Diff_triv)
apply (blast intro: leadsTo_weaken_L dest: constrains_imp_subset)
done

lemma psp2:
     "[| F ∈ A leadsTo A'; F ∈ B co B' |]
    ==> F ∈ (B' ∩ A) leadsTo ((B ∩ A') ∪ (B' - B))"
by (simp (no_asm_simp) add: psp Int_ac)

lemma psp_unless:
   "[| F ∈ A leadsTo A';  F ∈ B unless B' |]
    ==> F ∈ (A ∩ B) leadsTo ((A' ∩ B) ∪ B')"

apply (unfold unless_def)
apply (drule psp, assumption)
```

```
apply (blast intro: leadsTo_weaken)
done
```

3.5 Proving the induction rules

```
lemma leadsTo_wf_induct_lemma:
     "[| wf r;
         ∀m. F ∈ (A ∩ f-‘{m}) leadsTo
                     ((A ∩ f-‘(r^-1 ‘‘ {m})) ∪ B) |]
      ==> F ∈ (A ∩ f-‘{m}) leadsTo B"
apply (erule_tac a = m in wf_induct)
apply (subgoal_tac "F ∈ (A ∩ (f -‘ (r^-1 ‘‘ {x}))) leadsTo B")
 apply (blast intro: leadsTo_cancel1 leadsTo_Un_duplicate)
apply (subst vimage_eq_UN)
apply (simp only: UN_simps [symmetric])
apply (blast intro: leadsTo_UN)
done


lemma leadsTo_wf_induct:
     "[| wf r;
         ∀m. F ∈ (A ∩ f-‘{m}) leadsTo
                     ((A ∩ f-‘(r^-1 ‘‘ {m})) ∪ B) |]
      ==> F ∈ A leadsTo B"
apply (rule_tac t = A in subst)
 defer 1
 apply (rule leadsTo_UN)
 apply (erule leadsTo_wf_induct_lemma)
 apply assumption
apply fast
done


lemma bounded_induct:
     "[| wf r;
         ∀m ∈ I. F ∈ (A ∩ f-‘{m}) leadsTo
                       ((A ∩ f-‘(r^-1 ‘‘ {m})) ∪ B) |]
      ==> F ∈ A leadsTo ((A - (f-‘I)) ∪ B)"
apply (erule leadsTo_wf_induct, safe)
apply (case_tac "m ∈ I")
apply (blast intro: leadsTo_weaken)
apply (blast intro: subset_imp_leadsTo)
done


lemma lessThan_induct:
     "[| !!m::nat. F ∈ (A ∩ f-‘{m}) leadsTo ((A ∩ f-‘{..<m}) ∪ B) |]
      ==> F ∈ A leadsTo B"
apply (rule wf_less_than [THEN leadsTo_wf_induct])
apply (simp (no_asm_simp))
apply blast
done
```

```
lemma lessThan_bounded_induct:
     "!!l::nat. [| ∀m ∈ greaterThan l.
           F ∈ (A ∩ f-`{m}) leadsTo ((A ∩ f-`(lessThan m)) ∪ B) |]
      ==> F ∈ A leadsTo ((A ∩ (f-`(atMost l))) ∪ B)"
apply (simp only: Diff_eq [symmetric] vimage_Compl Compl_greaterThan [symmetric])
apply (rule wf_less_than [THEN bounded_induct])
apply (simp (no_asm_simp))
done

lemma greaterThan_bounded_induct:
     "(!!l::nat. ∀m ∈ lessThan l.
                F ∈ (A ∩ f-`{m}) leadsTo ((A ∩ f-`(greaterThan m)) ∪ B))
      ==> F ∈ A leadsTo ((A ∩ (f-`(atLeast l))) ∪ B)"
apply (rule_tac f = f and f1 = "%k. l - k"
       in wf_less_than [THEN wf_inv_image, THEN leadsTo_wf_induct])
apply (simp (no_asm) add:Image_singleton)
apply clarify
apply (case_tac "m<l")
 apply (blast intro: leadsTo_weaken_R diff_less_mono2)
apply (blast intro: not_le_imp_less subset_imp_leadsTo)
done
```

3.6 wlt

Misra's property W3

```
lemma wlt_leadsTo: "F ∈ (wlt F B) leadsTo B"
apply (unfold wlt_def)
apply (blast intro!: leadsTo_Union)
done

lemma leadsTo_subset: "F ∈ A leadsTo B ==> A ⊆ wlt F B"
apply (unfold wlt_def)
apply (blast intro!: leadsTo_Union)
done
```

Misra's property W2

```
lemma leadsTo_eq_subset_wlt: "F ∈ A leadsTo B = (A ⊆ wlt F B)"
by (blast intro!: leadsTo_subset wlt_leadsTo [THEN leadsTo_weaken_L])
```

Misra's property W4

```
lemma wlt_increasing: "B ⊆ wlt F B"
apply (simp (no_asm_simp) add: leadsTo_eq_subset_wlt [symmetric] subset_imp_leadsTo)
done
```

Used in the Trans case below

```
lemma lemma1:
   "[| B ⊆ A2;
       F ∈ (A1 - B) co (A1 ∪ B);
       F ∈ (A2 - C) co (A2 ∪ C) |]
    ==> F ∈ (A1 ∪ A2 - C) co (A1 ∪ A2 ∪ C)"
by (unfold constrains_def, clarify,  blast)
```

Lemma (1,2,3) of Misra's draft book, Chapter 4, "Progress"

```
lemma leadsTo_123:
     "F ∈ A leadsTo A'
      ==> ∃B. A ⊆ B & F ∈ B leadsTo A' & F ∈ (B-A') co (B ∪ A')"
apply (erule leadsTo_induct)
```

Basis

```
  apply (blast dest: ensuresD)
```

Trans

```
 apply clarify
 apply (rule_tac x = "Ba ∪ Bb" in exI)
 apply (blast intro: lemma1 leadsTo_Un_Un leadsTo_cancel1 leadsTo_Un_duplicate)
```

Union

```
apply (clarify dest!: ball_conj_distrib [THEN iffD1] bchoice)
apply (rule_tac x = "⋃A ∈ S. f A" in exI)
apply (auto intro: leadsTo_UN)

apply (rule_tac I1=S and A1="%i. f i - B" and A'1="%i. f i ∪ B"
       in constrains_UN [THEN constrains_weaken], auto)
done
```

Misra's property W5

```
lemma wlt_constrains_wlt: "F ∈ (wlt F B - B) co (wlt F B)"
proof -
  from wlt_leadsTo [of F B, THEN leadsTo_123]
  show ?thesis
  proof (elim exE conjE)

    fix C
    assume wlt: "wlt F B ⊆ C"
       and lt:  "F ∈ C leadsTo B"
       and co:  "F ∈ C - B co C ∪ B"
    have eq: "C = wlt F B"
    proof -
      from lt and wlt show ?thesis
           by (blast dest: leadsTo_eq_subset_wlt [THEN iffD1])
    qed
    from co show ?thesis by (simp add: eq wlt_increasing Un_absorb2)
  qed
qed
```

3.7 Completion: Binary and General Finite versions

```
lemma completion_lemma :
     "[| W = wlt F (B' ∪ C);
       F ∈ A leadsTo (A' ∪ C);  F ∈ A' co (A' ∪ C);
       F ∈ B leadsTo (B' ∪ C);  F ∈ B' co (B' ∪ C) |]
    ==> F ∈ (A ∩ B) leadsTo ((A' ∩ B') ∪ C)"
apply (subgoal_tac "F ∈ (W-C) co (W ∪ B' ∪ C) ")
 prefer 2
 apply (blast intro: wlt_constrains_wlt [THEN [2] constrains_Un,
```

```
                                        THEN constrains_weaken])
apply (subgoal_tac "F ∈ (W-C) co W")
 prefer 2
 apply (simp add: wlt_increasing Un_assoc Un_absorb2)
apply (subgoal_tac "F ∈ (A ∩ W - C) leadsTo (A' ∩ W ∪ C) ")
 prefer 2 apply (blast intro: wlt_leadsTo psp [THEN leadsTo_weaken])

apply (subgoal_tac "F ∈ (A' ∩ W ∪ C) leadsTo (A' ∩ B' ∪ C) ")
 prefer 2
 apply (rule leadsTo_Un_duplicate2)
 apply (blast intro: leadsTo_Un_Un wlt_leadsTo
                     [THEN psp2, THEN leadsTo_weaken] leadsTo_refl)
apply (drule leadsTo_Diff)
apply (blast intro: subset_imp_leadsTo)
apply (subgoal_tac "A ∩ B ⊆ A ∩ W")
 prefer 2
 apply (blast dest!: leadsTo_subset intro!: subset_refl [THEN Int_mono])
apply (blast intro: leadsTo_Trans subset_imp_leadsTo)
done

lemmas completion = completion_lemma [OF refl]

lemma finite_completion_lemma:
     "finite I ==> (∀i ∈ I. F ∈ (A i) leadsTo (A' i ∪ C)) -->
                   (∀i ∈ I. F ∈ (A' i) co (A' i ∪ C)) -->
                   F ∈ (⋂i ∈ I. A i) leadsTo ((⋂i ∈ I. A' i) ∪ C)"
apply (erule finite_induct, auto)
apply (rule completion)
   prefer 4
   apply (simp only: INT_simps [symmetric])
   apply (rule constrains_INT, auto)
done

lemma finite_completion:
     "[| finite I;
         !!i. i ∈ I ==> F ∈ (A i) leadsTo (A' i ∪ C);
         !!i. i ∈ I ==> F ∈ (A' i) co (A' i ∪ C) |]
      ==> F ∈ (⋂i ∈ I. A i) leadsTo ((⋂i ∈ I. A' i) ∪ C)"
by (blast intro: finite_completion_lemma [THEN mp, THEN mp])

lemma stable_completion:
     "[| F ∈ A leadsTo A';  F ∈ stable A';
         F ∈ B leadsTo B';  F ∈ stable B' |]
    ==> F ∈ (A ∩ B) leadsTo (A' ∩ B')"
apply (unfold stable_def)
apply (rule_tac C1 = "{}" in completion [THEN leadsTo_weaken_R])
apply (force+)
done

lemma finite_stable_completion:
     "[| finite I;
         !!i. i ∈ I ==> F ∈ (A i) leadsTo (A' i);
         !!i. i ∈ I ==> F ∈ stable (A' i) |]
      ==> F ∈ (⋂i ∈ I. A i) leadsTo (⋂i ∈ I. A' i)"
```

```
apply (unfold stable_def)
apply (rule_tac C1 = "{}" in finite_completion [THEN leadsTo_weaken_R])
apply (simp_all (no_asm_simp))
apply blast+
done

end
```

4 Weak Safety

```
theory Constrains imports UNITY begin



inductive_set
  traces :: "['a set, ('a * 'a)set set] => ('a * 'a list) set"
  for init :: "'a set" and acts :: "('a * 'a)set set"
  where

    Init:  "s ∈ init ==> (s,[]) ∈ traces init acts"

  | Acts:  "[| act ∈ acts;  (s,evs) ∈ traces init acts;  (s,s') ∈ act |]
            ==> (s', s#evs) ∈ traces init acts"


inductive_set
  reachable :: "'a program => 'a set"
  for F :: "'a program"
  where
    Init:  "s ∈ Init F ==> s ∈ reachable F"

  | Acts:  "[| act ∈ Acts F;  s ∈ reachable F;  (s,s') ∈ act |]
            ==> s' ∈ reachable F"

definition Constrains :: "['a set, 'a set] => 'a program set" (infixl "Co" 60)
where
    "A Co B == {F. F ∈ (reachable F ∩ A)  co  B}"

definition Unless  :: "['a set, 'a set] => 'a program set" (infixl "Unless"
60) where
    "A Unless B == (A-B) Co (A ∪ B)"

definition Stable     :: "'a set => 'a program set" where
    "Stable A == A Co A"


definition Always :: "'a set => 'a program set" where
    "Always A == {F. Init F ⊆ A} ∩ Stable A"


definition Increasing :: "['a => 'b::{order}] => 'a program set" where
    "Increasing f == ⋂z. Stable {s. z ≤ f s}"
```

4.1 traces and reachable

lemma *reachable_equiv_traces:*
"reachable F = {s. ∃evs. (s,evs) ∈ traces (Init F) (Acts F)}"
apply *safe*
apply *(erule_tac [2] traces.induct)*
apply *(erule reachable.induct)*
apply *(blast intro: reachable.intros traces.intros)+*
done

lemma *Init_subset_reachable: "Init F ⊆ reachable F"*
by *(blast intro: reachable.intros)*

lemma *stable_reachable [intro!,simp]:*
"Acts G ⊆ Acts F ==> G ∈ stable (reachable F)"
by *(blast intro: stableI constrainsI reachable.intros)*

lemma *invariant_reachable: "F ∈ invariant (reachable F)"*
apply *(simp add: invariant_def)*
apply *(blast intro: reachable.intros)*
done

lemma *invariant_includes_reachable: "F ∈ invariant A ==> reachable F ⊆ A"*
apply *(simp add: stable_def constrains_def invariant_def)*
apply *(rule subsetI)*
apply *(erule reachable.induct)*
apply *(blast intro: reachable.intros)+*
done

4.2 Co

lemmas *constrains_reachable_Int =*
subset_refl [THEN stable_reachable [unfolded stable_def], THEN constrains_Int]

lemma *Constrains_eq_constrains:*
"A Co B = {F. F ∈ (reachable F ∩ A) co (reachable F ∩ B)}"
apply *(unfold Constrains_def)*
apply *(blast dest: constrains_reachable_Int intro: constrains_weaken)*
done

lemma *constrains_imp_Constrains: "F ∈ A co A' ==> F ∈ A Co A'"*
apply *(unfold Constrains_def)*
apply *(blast intro: constrains_weaken_L)*
done

lemma *stable_imp_Stable: "F ∈ stable A ==> F ∈ Stable A"*
apply *(unfold stable_def Stable_def)*
apply *(erule constrains_imp_Constrains)*
done

lemma *ConstrainsI:*
"(!!act s s'. [| act ∈ Acts F; (s,s') ∈ act; s ∈ A |] ==> s' ∈ A')

```
     ==> F ∈ A Co A'"
apply (rule constrains_imp_Constrains)
apply (blast intro: constrainsI)
done

lemma Constrains_empty [iff]: "F ∈ {} Co B"
by (unfold Constrains_def constrains_def, blast)

lemma Constrains_UNIV [iff]: "F ∈ A Co UNIV"
by (blast intro: ConstrainsI)

lemma Constrains_weaken_R:
    "[| F ∈ A Co A'; A'<=B' |] ==> F ∈ A Co B'"
apply (unfold Constrains_def)
apply (blast intro: constrains_weaken_R)
done

lemma Constrains_weaken_L:
    "[| F ∈ A Co A'; B ⊆ A |] ==> F ∈ B Co A'"
apply (unfold Constrains_def)
apply (blast intro: constrains_weaken_L)
done

lemma Constrains_weaken:
   "[| F ∈ A Co A'; B ⊆ A; A'<=B' |] ==> F ∈ B Co B'"
apply (unfold Constrains_def)
apply (blast intro: constrains_weaken)
done



lemma Constrains_Un:
    "[| F ∈ A Co A'; F ∈ B Co B' |] ==> F ∈ (A ∪ B) Co (A' ∪ B')"
apply (unfold Constrains_def)
apply (blast intro: constrains_Un [THEN constrains_weaken])
done

lemma Constrains_UN:
  assumes Co: "!!i. i ∈ I ==> F ∈ (A i) Co (A' i)"
  shows "F ∈ (⋃i ∈ I. A i) Co (⋃i ∈ I. A' i)"
apply (unfold Constrains_def)
apply (rule CollectI)
apply (rule Co [unfolded Constrains_def, THEN CollectD, THEN constrains_UN,

                THEN constrains_weaken],   auto)
done



lemma Constrains_Int:
    "[| F ∈ A Co A'; F ∈ B Co B' |] ==> F ∈ (A ∩ B) Co (A' ∩ B')"
apply (unfold Constrains_def)
apply (blast intro: constrains_Int [THEN constrains_weaken])
```

done

lemma *Constrains_INT:*
  assumes *Co: "!!i. i ∈ I ==> F ∈ (A i) Co (A' i)"*
  shows *"F ∈ (⋂i ∈ I. A i) Co (⋂i ∈ I. A' i)"*
apply *(unfold Constrains_def)*
apply *(rule CollectI)*
apply *(rule Co [unfolded Constrains_def, THEN CollectD, THEN constrains_INT,*

THEN constrains_weaken], auto)
done

lemma *Constrains_imp_subset: "F ∈ A Co A' ==> reachable F ∩ A ⊆ A'"*
by *(simp add: constrains_imp_subset Constrains_def)*

lemma *Constrains_trans: "[| F ∈ A Co B; F ∈ B Co C |] ==> F ∈ A Co C"*
apply *(simp add: Constrains_eq_constrains)*
apply *(blast intro: constrains_trans constrains_weaken)*
done

lemma *Constrains_cancel:*
"[| F ∈ A Co (A' ∪ B); F ∈ B Co B' |] ==> F ∈ A Co (A' ∪ B')"
apply *(simp add: Constrains_eq_constrains constrains_def)*
apply *best*
done

4.3 Stable

lemma *Stable_eq: "[| F ∈ Stable A; A = B |] ==> F ∈ Stable B"*
by *blast*

lemma *Stable_eq_stable: "(F ∈ Stable A) = (F ∈ stable (reachable F ∩ A))"*
by *(simp add: Stable_def Constrains_eq_constrains stable_def)*

lemma *StableI: "F ∈ A Co A ==> F ∈ Stable A"*
by *(unfold Stable_def, assumption)*

lemma *StableD: "F ∈ Stable A ==> F ∈ A Co A"*
by *(unfold Stable_def, assumption)*

lemma *Stable_Un:*
"[| F ∈ Stable A; F ∈ Stable A' |] ==> F ∈ Stable (A ∪ A')"
apply *(unfold Stable_def)*
apply *(blast intro: Constrains_Un)*
done

lemma *Stable_Int:*
"[| F ∈ Stable A; F ∈ Stable A' |] ==> F ∈ Stable (A ∩ A')"
apply *(unfold Stable_def)*
apply *(blast intro: Constrains_Int)*
done

lemma *Stable_Constrains_Un:*
"[| F ∈ Stable C; F ∈ A Co (C ∪ A') |]

```
    ==> F ∈ (C ∪ A) Co (C ∪ A')"
apply (unfold Stable_def)
apply (blast intro: Constrains_Un [THEN Constrains_weaken])
done

lemma Stable_Constrains_Int:
    "[| F ∈ Stable C; F ∈ (C ∩ A) Co A' |]
     ==> F ∈ (C ∩ A) Co (C ∩ A')"
apply (unfold Stable_def)
apply (blast intro: Constrains_Int [THEN Constrains_weaken])
done

lemma Stable_UN:
    "(!!i. i ∈ I ==> F ∈ Stable (A i)) ==> F ∈ Stable (⋃i ∈ I. A i)"
by (simp add: Stable_def Constrains_UN)

lemma Stable_INT:
    "(!!i. i ∈ I ==> F ∈ Stable (A i)) ==> F ∈ Stable (⋂i ∈ I. A i)"
by (simp add: Stable_def Constrains_INT)

lemma Stable_reachable: "F ∈ Stable (reachable F)"
by (simp add: Stable_eq_stable)
```

4.4 Increasing

```
lemma IncreasingD:
     "F ∈ Increasing f ==> F ∈ Stable {s. x ≤ f s}"
by (unfold Increasing_def, blast)

lemma mono_Increasing_o:
     "mono g ==> Increasing f ⊆ Increasing (g o f)"
apply (simp add: Increasing_def Stable_def Constrains_def stable_def
                 constrains_def)
apply (blast intro: monoD order_trans)
done

lemma strict_IncreasingD:
     "!!z::nat. F ∈ Increasing f ==> F ∈ Stable {s. z < f s}"
by (simp add: Increasing_def Suc_le_eq [symmetric])

lemma increasing_imp_Increasing:
     "F ∈ increasing f ==> F ∈ Increasing f"
apply (unfold increasing_def Increasing_def)
apply (blast intro: stable_imp_Stable)
done

lemmas Increasing_constant = increasing_constant [THEN increasing_imp_Increasing,
iff]
```

4.5 The Elimination Theorem

```
lemma Elimination:
    "[| ∀m. F ∈ {s. s x = m} Co (B m) |]
     ==> F ∈ {s. s x ∈ M} Co (⋃m ∈ M. B m)"
```

by *(unfold Constrains_def constrains_def, blast)*

lemma *Elimination_sing:*
"(∀m. F ∈ {m} Co (B m)) ==> F ∈ M Co (⋃m ∈ M. B m)"
by *(unfold Constrains_def constrains_def, blast)*

4.6 Specialized laws for handling Always

lemma *AlwaysI: "[| Init F ⊆ A; F ∈ Stable A |] ==> F ∈ Always A"*
by *(simp add: Always_def)*

lemma *AlwaysD: "F ∈ Always A ==> Init F ⊆ A & F ∈ Stable A"*
by *(simp add: Always_def)*

lemmas *AlwaysE = AlwaysD [THEN conjE]*
lemmas *Always_imp_Stable = AlwaysD [THEN conjunct2]*

lemma *Always_includes_reachable: "F ∈ Always A ==> reachable F ⊆ A"*
apply *(simp add: Stable_def Constrains_def constrains_def Always_def)*
apply *(rule subsetI)*
apply *(erule reachable.induct)*
apply *(blast intro: reachable.intros)+*
done

lemma *invariant_imp_Always:*
"F ∈ invariant A ==> F ∈ Always A"
apply *(unfold Always_def invariant_def Stable_def stable_def)*
apply *(blast intro: constrains_imp_Constrains)*
done

lemmas *Always_reachable = invariant_reachable [THEN invariant_imp_Always]*

lemma *Always_eq_invariant_reachable:*
"Always A = {F. F ∈ invariant (reachable F ∩ A)}"
apply *(simp add: Always_def invariant_def Stable_def Constrains_eq_constrains*
stable_def)
apply *(blast intro: reachable.intros)*
done

lemma *Always_eq_includes_reachable: "Always A = {F. reachable F ⊆ A}"*
by *(auto dest: invariant_includes_reachable simp add: Int_absorb2 invariant_reachable*
Always_eq_invariant_reachable)

lemma *Always_UNIV_eq [simp]: "Always UNIV = UNIV"*
by *(auto simp add: Always_eq_includes_reachable)*

lemma *UNIV_AlwaysI: "UNIV ⊆ A ==> F ∈ Always A"*
by *(auto simp add: Always_eq_includes_reachable)*

lemma *Always_eq_UN_invariant: "Always A = (⋃I ∈ Pow A. invariant I)"*

apply *(simp add: Always_eq_includes_reachable)*
apply *(blast intro: invariantI Init_subset_reachable [THEN subsetD]*
invariant_includes_reachable [THEN subsetD])
done

lemma *Always_weaken: "[| F ∈ Always A; A ⊆ B |] ==> F ∈ Always B"*
by *(auto simp add: Always_eq_includes_reachable)*

4.7 "Co" rules involving Always

lemma *Always_Constrains_pre:*
"F ∈ Always INV ==> (F ∈ (INV ∩ A) Co A') = (F ∈ A Co A')"
by *(simp add: Always_includes_reachable [THEN Int_absorb2] Constrains_def*

Int_assoc [symmetric])

lemma *Always_Constrains_post:*
"F ∈ Always INV ==> (F ∈ A Co (INV ∩ A')) = (F ∈ A Co A')"
by *(simp add: Always_includes_reachable [THEN Int_absorb2]*
Constrains_eq_constrains Int_assoc [symmetric])

lemmas *Always_ConstrainsI = Always_Constrains_pre [THEN iffD1]*

lemmas *Always_ConstrainsD = Always_Constrains_post [THEN iffD2]*

lemma *Always_Constrains_weaken:*
"[| F ∈ Always C; F ∈ A Co A';
C ∩ B ⊆ A; C ∩ A' ⊆ B' |]
==> F ∈ B Co B'"
apply *(rule Always_ConstrainsI, assumption)*
apply *(drule Always_ConstrainsD, assumption)*
apply *(blast intro: Constrains_weaken)*
done

lemma *Always_Int_distrib: "Always (A ∩ B) = Always A ∩ Always B"*
by *(auto simp add: Always_eq_includes_reachable)*

lemma *Always_INT_distrib: "Always (⋂(A ‘ I)) = (⋂i ∈ I. Always (A i))"*
by *(auto simp add: Always_eq_includes_reachable)*

lemma *Always_Int_I:*
"[| F ∈ Always A; F ∈ Always B |] ==> F ∈ Always (A ∩ B)"
by *(simp add: Always_Int_distrib)*

lemma *Always_Compl_Un_eq:*
"F ∈ Always A ==> (F ∈ Always (-A ∪ B)) = (F ∈ Always B)"
by *(auto simp add: Always_eq_includes_reachable)*

lemmas *Always_thin = thin_rl [of "F ∈ Always A"]* **for** *F A*

4.8 Totalize

lemma *reachable_imp_reachable_tot:*
"s ∈ reachable F ==> s ∈ reachable (totalize F)"
apply *(erule reachable.induct)*
apply *(rule reachable.Init)*
apply *simp*
apply *(rule_tac act = "totalize_act act"* **in** *reachable.Acts)*
apply *(auto simp add: totalize_act_def)*
done

lemma *reachable_tot_imp_reachable:*
"s ∈ reachable (totalize F) ==> s ∈ reachable F"
apply *(erule reachable.induct)*
apply *(rule reachable.Init, simp)*
apply *(force simp add: totalize_act_def intro: reachable.Acts)*
done

lemma *reachable_tot_eq [simp]: "reachable (totalize F) = reachable F"*
by *(blast intro: reachable_imp_reachable_tot reachable_tot_imp_reachable)*

lemma *totalize_Constrains_iff [simp]: "(totalize F ∈ A Co B) = (F ∈ A Co B)"*
by *(simp add: Constrains_def)*

lemma *totalize_Stable_iff [simp]: "(totalize F ∈ Stable A) = (F ∈ Stable A)"*
by *(simp add: Stable_def)*

lemma *totalize_Always_iff [simp]: "(totalize F ∈ Always A) = (F ∈ Always A)"*
by *(simp add: Always_def)*

end

5 Weak Progress

theory *SubstAx* **imports** *WFair Constrains* **begin**

definition *Ensures :: "['a set, 'a set] => 'a program set"* (**infixl** *"Ensures" 60)* **where**
"A Ensures B == {F. F ∈ (reachable F ∩ A) ensures B}"

definition *LeadsTo :: "['a set, 'a set] => 'a program set"* (**infixl** *"LeadsTo" 60)* **where**
"A LeadsTo B == {F. F ∈ (reachable F ∩ A) leadsTo B}"

notation *LeadsTo* (**infixl** *"⟼w" 60)*

Resembles the previous definition of LeadsTo

lemma *LeadsTo_eq_leadsTo:*
```
    "A LeadsTo B = {F. F ∈ (reachable F ∩ A) leadsTo (reachable F ∩ B)}"
```
apply *(unfold LeadsTo_def)*
apply *(blast dest: psp_stable2 intro: leadsTo_weaken)*
done

5.1 Specialized laws for handling invariants

lemma *Always_LeadsTo_pre:*
```
    "F ∈ Always INV ==> (F ∈ (INV ∩ A) LeadsTo A') = (F ∈ A LeadsTo A')"
```
by *(simp add: LeadsTo_def Always_eq_includes_reachable Int_absorb2*
Int_assoc [symmetric])

lemma *Always_LeadsTo_post:*
```
    "F ∈ Always INV ==> (F ∈ A LeadsTo (INV ∩ A')) = (F ∈ A LeadsTo A')"
```
by *(simp add: LeadsTo_eq_leadsTo Always_eq_includes_reachable Int_absorb2*

Int_assoc [symmetric])

lemmas *Always_LeadsToI = Always_LeadsTo_pre [THEN iffD1]*

lemmas *Always_LeadsToD = Always_LeadsTo_post [THEN iffD2]*

5.2 Introduction rules: Basis, Trans, Union

lemma *leadsTo_imp_LeadsTo: "F ∈ A leadsTo B ==> F ∈ A LeadsTo B"*
apply *(simp add: LeadsTo_def)*
apply *(blast intro: leadsTo_weaken_L)*
done

lemma *LeadsTo_Trans:*
```
    "[| F ∈ A LeadsTo B;  F ∈ B LeadsTo C |] ==> F ∈ A LeadsTo C"
```
apply *(simp add: LeadsTo_eq_leadsTo)*
apply *(blast intro: leadsTo_Trans)*
done

lemma *LeadsTo_Union:*
```
    "(!!A. A ∈ S ==> F ∈ A LeadsTo B) ==> F ∈ (⋃S) LeadsTo B"
```
apply *(simp add: LeadsTo_def)*
apply *(subst Int_Union)*
apply *(blast intro: leadsTo_UN)*
done

5.3 Derived rules

lemma *LeadsTo_UNIV [simp]: "F ∈ A LeadsTo UNIV"*
by *(simp add: LeadsTo_def)*

Useful with cancellation, disjunction

lemma *LeadsTo_Un_duplicate:*

```
    "F ∈ A LeadsTo (A' ∪ A') ==> F ∈ A LeadsTo A'"
by (simp add: Un_ac)

lemma LeadsTo_Un_duplicate2:
    "F ∈ A LeadsTo (A' ∪ C ∪ C) ==> F ∈ A LeadsTo (A' ∪ C)"
by (simp add: Un_ac)

lemma LeadsTo_UN:
    "(!!i. i ∈ I ==> F ∈ (A i) LeadsTo B) ==> F ∈ (⋃i ∈ I. A i) LeadsTo
B"
apply (blast intro: LeadsTo_Union)
done
```

Binary union introduction rule

```
lemma LeadsTo_Un:
    "[| F ∈ A LeadsTo C; F ∈ B LeadsTo C |] ==> F ∈ (A ∪ B) LeadsTo C"
  using LeadsTo_UN [of "{A, B}" F id C] by auto
```

Lets us look at the starting state

```
lemma single_LeadsTo_I:
    "(!!s. s ∈ A ==> F ∈ {s} LeadsTo B) ==> F ∈ A LeadsTo B"
by (subst UN_singleton [symmetric], rule LeadsTo_UN, blast)

lemma subset_imp_LeadsTo: "A ⊆ B ==> F ∈ A LeadsTo B"
apply (simp add: LeadsTo_def)
apply (blast intro: subset_imp_leadsTo)
done

lemmas empty_LeadsTo = empty_subsetI [THEN subset_imp_LeadsTo, simp]

lemma LeadsTo_weaken_R:
    "[| F ∈ A LeadsTo A';  A' ⊆ B' |] ==> F ∈ A LeadsTo B'"
apply (simp add: LeadsTo_def)
apply (blast intro: leadsTo_weaken_R)
done

lemma LeadsTo_weaken_L:
    "[| F ∈ A LeadsTo A';  B ⊆ A |]
     ==> F ∈ B LeadsTo A'"
apply (simp add: LeadsTo_def)
apply (blast intro: leadsTo_weaken_L)
done

lemma LeadsTo_weaken:
    "[| F ∈ A LeadsTo A';
        B  ⊆ A;   A' ⊆ B' |]
     ==> F ∈ B LeadsTo B'"
by (blast intro: LeadsTo_weaken_R LeadsTo_weaken_L LeadsTo_Trans)

lemma Always_LeadsTo_weaken:
    "[| F ∈ Always C;  F ∈ A LeadsTo A';
        C ∩ B ⊆ A;   C ∩ A' ⊆ B' |]
     ==> F ∈ B LeadsTo B'"
by (blast dest: Always_LeadsToI intro: LeadsTo_weaken intro: Always_LeadsToD)
```

lemma *LeadsTo_Un_post: "F ∈ A LeadsTo B ==> F ∈ (A ∪ B) LeadsTo B"*
by *(blast intro: LeadsTo_Un subset_imp_LeadsTo)*

lemma *LeadsTo_Trans_Un:*
"[| F ∈ A LeadsTo B; F ∈ B LeadsTo C |]
==> F ∈ (A ∪ B) LeadsTo C"
by *(blast intro: LeadsTo_Un subset_imp_LeadsTo LeadsTo_weaken_L LeadsTo_Trans)*

lemma *LeadsTo_Un_distrib:*
"(F ∈ (A ∪ B) LeadsTo C) = (F ∈ A LeadsTo C & F ∈ B LeadsTo C)"
by *(blast intro: LeadsTo_Un LeadsTo_weaken_L)*

lemma *LeadsTo_UN_distrib:*
"(F ∈ (⋃i ∈ I. A i) LeadsTo B) = (∀i ∈ I. F ∈ (A i) LeadsTo B)"
by *(blast intro: LeadsTo_UN LeadsTo_weaken_L)*

lemma *LeadsTo_Union_distrib:*
"(F ∈ (⋃S) LeadsTo B) = (∀A ∈ S. F ∈ A LeadsTo B)"
by *(blast intro: LeadsTo_Union LeadsTo_weaken_L)*

lemma *LeadsTo_Basis: "F ∈ A Ensures B ==> F ∈ A LeadsTo B"*
by *(simp add: Ensures_def LeadsTo_def leadsTo_Basis)*

lemma *EnsuresI:*
"[| F ∈ (A-B) Co (A ∪ B); F ∈ transient (A-B) |]
==> F ∈ A Ensures B"
apply *(simp add: Ensures_def Constrains_eq_constrains)*
apply *(blast intro: ensuresI constrains_weaken transient_strengthen)*
done

lemma *Always_LeadsTo_Basis:*
"[| F ∈ Always INV;
F ∈ (INV ∩ (A-A')) Co (A ∪ A');
F ∈ transient (INV ∩ (A-A')) |]
==> F ∈ A LeadsTo A'"
apply *(rule Always_LeadsToI, assumption)*
apply *(blast intro: EnsuresI LeadsTo_Basis Always_ConstrainsD [THEN Constrains_weaken] transient_strengthen)*
done

Set difference: maybe combine with *leadsTo_weaken_L*?? This is the most useful form of the "disjunction" rule

lemma *LeadsTo_Diff:*
"[| F ∈ (A-B) LeadsTo C; F ∈ (A ∩ B) LeadsTo C |]
==> F ∈ A LeadsTo C"

by *(blast intro: LeadsTo_Un LeadsTo_weaken)*

lemma *LeadsTo_UN_UN:*
```
"(!! i. i ∈ I ==> F ∈ (A i) LeadsTo (A' i))
 ==> F ∈ (⋃i ∈ I. A i) LeadsTo (⋃i ∈ I. A' i)"
```
apply *(blast intro: LeadsTo_Union LeadsTo_weaken_R)*
done

Version with no index set

lemma *LeadsTo_UN_UN_noindex:*
```
"(!!i. F ∈ (A i) LeadsTo (A' i)) ==> F ∈ (⋃i. A i) LeadsTo (⋃i. A' i)"
```
by *(blast intro: LeadsTo_UN_UN)*

Version with no index set

lemma *all_LeadsTo_UN_UN:*
```
"∀i. F ∈ (A i) LeadsTo (A' i)
 ==> F ∈ (⋃i. A i) LeadsTo (⋃i. A' i)"
```
by *(blast intro: LeadsTo_UN_UN)*

Binary union version

lemma *LeadsTo_Un_Un:*
```
"[| F ∈ A LeadsTo A'; F ∈ B LeadsTo B' |]
       ==> F ∈ (A ∪ B) LeadsTo (A' ∪ B')"
```
by *(blast intro: LeadsTo_Un LeadsTo_weaken_R)*

lemma *LeadsTo_cancel2:*
```
"[| F ∈ A LeadsTo (A' ∪ B); F ∈ B LeadsTo B' |]
 ==> F ∈ A LeadsTo (A' ∪ B')"
```
by *(blast intro: LeadsTo_Un_Un subset_imp_LeadsTo LeadsTo_Trans)*

lemma *LeadsTo_cancel_Diff2:*
```
"[| F ∈ A LeadsTo (A' ∪ B); F ∈ (B-A') LeadsTo B' |]
 ==> F ∈ A LeadsTo (A' ∪ B')"
```
apply *(rule LeadsTo_cancel2)*
prefer *2* **apply** *assumption*
apply *(simp_all (no_asm_simp))*
done

lemma *LeadsTo_cancel1:*
```
"[| F ∈ A LeadsTo (B ∪ A'); F ∈ B LeadsTo B' |]
 ==> F ∈ A LeadsTo (B' ∪ A')"
```
apply *(simp add: Un_commute)*
apply *(blast intro!: LeadsTo_cancel2)*
done

lemma *LeadsTo_cancel_Diff1:*
```
"[| F ∈ A LeadsTo (B ∪ A'); F ∈ (B-A') LeadsTo B' |]
 ==> F ∈ A LeadsTo (B' ∪ A')"
```

```
apply (rule LeadsTo_cancel1)
prefer 2 apply assumption
apply (simp_all (no_asm_simp))
done
```

The impossibility law

The set "A" may be non-empty, but it contains no reachable states

```
lemma LeadsTo_empty: "[|F ∈ A LeadsTo {}; all_total F|] ==> F ∈ Always (-A)"
apply (simp add: LeadsTo_def Always_eq_includes_reachable)
apply (drule leadsTo_empty, auto)
done
```

5.4 PSP: Progress-Safety-Progress

Special case of PSP: Misra's "stable conjunction"

```
lemma PSP_Stable:
     "[| F ∈ A LeadsTo A';  F ∈ Stable B |]
      ==> F ∈ (A ∩ B) LeadsTo (A' ∩ B)"
apply (simp add: LeadsTo_eq_leadsTo Stable_eq_stable)
apply (drule psp_stable, assumption)
apply (simp add: Int_ac)
done

lemma PSP_Stable2:
     "[| F ∈ A LeadsTo A'; F ∈ Stable B |]
      ==> F ∈ (B ∩ A) LeadsTo (B ∩ A')"
by (simp add: PSP_Stable Int_ac)

lemma PSP:
     "[| F ∈ A LeadsTo A'; F ∈ B Co B' |]
      ==> F ∈ (A ∩ B') LeadsTo ((A' ∩ B) ∪ (B' - B))"
apply (simp add: LeadsTo_def Constrains_eq_constrains)
apply (blast dest: psp intro: leadsTo_weaken)
done

lemma PSP2:
     "[| F ∈ A LeadsTo A'; F ∈ B Co B' |]
      ==> F ∈ (B' ∩ A) LeadsTo ((B ∩ A') ∪ (B' - B))"
by (simp add: PSP Int_ac)

lemma PSP_Unless:
     "[| F ∈ A LeadsTo A'; F ∈ B Unless B' |]
      ==> F ∈ (A ∩ B) LeadsTo ((A' ∩ B) ∪ B')"
apply (unfold Unless_def)
apply (drule PSP, assumption)
apply (blast intro: LeadsTo_Diff LeadsTo_weaken subset_imp_LeadsTo)
done


lemma Stable_transient_Always_LeadsTo:
     "[| F ∈ Stable A;  F ∈ transient C;
         F ∈ Always (-A ∪ B ∪ C) |] ==> F ∈ A LeadsTo B"
```

```
apply (erule Always_LeadsTo_weaken)
apply (rule LeadsTo_Diff)
   prefer 2
   apply (erule
          transient_imp_leadsTo [THEN leadsTo_imp_LeadsTo, THEN PSP_Stable2])
   apply (blast intro: subset_imp_LeadsTo)+
done
```

5.5 Induction rules

```
lemma LeadsTo_wf_induct:
     "[| wf r;
         ∀m. F ∈ (A ∩ f-‘{m}) LeadsTo
                     ((A ∩ f-‘(r^-1 ‘‘ {m})) ∪ B) |]
      ==> F ∈ A LeadsTo B"
apply (simp add: LeadsTo_eq_leadsTo)
apply (erule leadsTo_wf_induct)
apply (blast intro: leadsTo_weaken)
done


lemma Bounded_induct:
     "[| wf r;
         ∀m ∈ I. F ∈ (A ∩ f-‘{m}) LeadsTo
                       ((A ∩ f-‘(r^-1 ‘‘ {m})) ∪ B) |]
      ==> F ∈ A LeadsTo ((A - (f-‘I)) ∪ B)"
apply (erule LeadsTo_wf_induct, safe)
apply (case_tac "m ∈ I")
apply (blast intro: LeadsTo_weaken)
apply (blast intro: subset_imp_LeadsTo)
done


lemma LessThan_induct:
     "(!!m::nat. F ∈ (A ∩ f-‘{m}) LeadsTo ((A ∩ f-‘(lessThan m)) ∪ B))
      ==> F ∈ A LeadsTo B"
by (rule wf_less_than [THEN LeadsTo_wf_induct], auto)
```

Integer version. Could generalize from 0 to any lower bound

```
lemma integ_0_le_induct:
     "[| F ∈ Always {s. (0::int) ≤ f s};
         !! z. F ∈ (A ∩ {s. f s = z}) LeadsTo
                     ((A ∩ {s. f s < z}) ∪ B) |]
      ==> F ∈ A LeadsTo B"
apply (rule_tac f = "nat o f" in LessThan_induct)
apply (simp add: vimage_def)
apply (rule Always_LeadsTo_weaken, assumption+)
apply (auto simp add: nat_eq_iff nat_less_iff)
done

lemma LessThan_bounded_induct:
     "!!l::nat. ∀m ∈ greaterThan l.
                    F ∈ (A ∩ f-‘{m}) LeadsTo ((A ∩ f-‘(lessThan m)) ∪ B)
           ==> F ∈ A LeadsTo ((A ∩ (f-‘(atMost l))) ∪ B)"
```

```
apply (simp only: Diff_eq [symmetric] vimage_Compl
                  Compl_greaterThan [symmetric])
apply (rule wf_less_than [THEN Bounded_induct], simp)
done

lemma GreaterThan_bounded_induct:
     "!!l::nat. ∀m ∈ lessThan l.
                F ∈ (A ∩ f-‘{m}) LeadsTo ((A ∩ f-‘(greaterThan m)) ∪ B)
      ==> F ∈ A LeadsTo ((A ∩ (f-‘(atLeast l))) ∪ B)"
apply (rule_tac f = f and f1 = "%k. l - k"
       in wf_less_than [THEN wf_inv_image, THEN LeadsTo_wf_induct])
apply (simp add: Image_singleton, clarify)
apply (case_tac "m<l")
 apply (blast intro: LeadsTo_weaken_R diff_less_mono2)
apply (blast intro: not_le_imp_less subset_imp_LeadsTo)
done
```

5.6 Completion: Binary and General Finite versions

```
lemma Completion:
     "[| F ∈ A LeadsTo (A' ∪ C);  F ∈ A' Co (A' ∪ C);
         F ∈ B LeadsTo (B' ∪ C);  F ∈ B' Co (B' ∪ C) |]
      ==> F ∈ (A ∩ B) LeadsTo ((A' ∩ B') ∪ C)"
apply (simp add: LeadsTo_eq_leadsTo Constrains_eq_constrains Int_Un_distrib)
apply (blast intro: completion leadsTo_weaken)
done

lemma Finite_completion_lemma:
     "finite I
      ==> (∀i ∈ I. F ∈ (A i) LeadsTo (A' i ∪ C)) -->
          (∀i ∈ I. F ∈ (A' i) Co (A' i ∪ C)) -->
          F ∈ (⋂i ∈ I. A i) LeadsTo ((⋂i ∈ I. A' i) ∪ C)"
apply (erule finite_induct, auto)
apply (rule Completion)
   prefer 4
   apply (simp only: INT_simps [symmetric])
   apply (rule Constrains_INT, auto)
done

lemma Finite_completion:
     "[| finite I;
         !!i. i ∈ I ==> F ∈ (A i) LeadsTo (A' i ∪ C);
         !!i. i ∈ I ==> F ∈ (A' i) Co (A' i ∪ C) |]
      ==> F ∈ (⋂i ∈ I. A i) LeadsTo ((⋂i ∈ I. A' i) ∪ C)"
by (blast intro: Finite_completion_lemma [THEN mp, THEN mp])

lemma Stable_completion:
     "[| F ∈ A LeadsTo A';  F ∈ Stable A';
         F ∈ B LeadsTo B';  F ∈ Stable B' |]
      ==> F ∈ (A ∩ B) LeadsTo (A' ∩ B')"
apply (unfold Stable_def)
apply (rule_tac C1 = "{}" in Completion [THEN LeadsTo_weaken_R])
apply (force+)
done
```

```
lemma Finite_stable_completion:
     "[| finite I;
         !!i. i ∈ I ==> F ∈ (A i) LeadsTo (A' i);
         !!i. i ∈ I ==> F ∈ Stable (A' i) |]
      ==> F ∈ (⋂i ∈ I. A i) LeadsTo (⋂i ∈ I. A' i)"
apply (unfold Stable_def)
apply (rule_tac C1 = "{}" in Finite_completion [THEN LeadsTo_weaken_R])
apply (simp_all, blast+)
done

end
```

6 The Detects Relation

```
theory Detects imports FP SubstAx begin

definition Detects :: "['a set, 'a set] => 'a program set"  (infixl "Detects"
60)
  where "A Detects B = (Always (-A ∪ B)) ∩ (B LeadsTo A)"

definition Equality :: "['a set, 'a set] => 'a set"  (infixl "<==>" 60)
  where "A <==> B = (-A ∪ B) ∩ (A ∪ -B)"



lemma Always_at_FP:
     "[|F ∈ A LeadsTo B; all_total F|] ==> F ∈ Always (-((FP F) ∩ A ∩ -B))"
supply [[simproc del: boolean_algebra_cancel_inf]] inf_compl_bot_right[simp
del]
apply (rule LeadsTo_empty)
apply (subgoal_tac "F ∈ (FP F ∩ A ∩ - B) LeadsTo (B ∩ (FP F ∩ -B))")
apply (subgoal_tac [2] " (FP F ∩ A ∩ - B) = (A ∩ (FP F ∩ -B))")
apply (subgoal_tac "(B ∩ (FP F ∩ -B)) = {}")
apply auto
apply (blast intro: PSP_Stable stable_imp_Stable stable_FP_Int)
done


lemma Detects_Trans:
     "[| F ∈ A Detects B; F ∈ B Detects C |] ==> F ∈ A Detects C"
apply (unfold Detects_def Int_def)
apply (simp (no_asm))
apply safe
apply (rule_tac [2] LeadsTo_Trans, auto)
apply (subgoal_tac "F ∈ Always ((-A ∪ B) ∩ (-B ∪ C))")
 apply (blast intro: Always_weaken)
apply (simp add: Always_Int_distrib)
done

lemma Detects_refl: "F ∈ A Detects A"
apply (unfold Detects_def)
```

apply *(simp (no_asm) add: Un_commute Compl_partition subset_imp_LeadsTo)*
done

lemma *Detects_eq_Un: "(A<==>B) = (A ∩ B) ∪ (-A ∩ -B)"*
by *(unfold Equality_def, blast)*

lemma *Detects_antisym:*
"[| F ∈ A Detects B; F ∈ B Detects A|] ==> F ∈ Always (A <==> B)"
apply *(unfold Detects_def Equality_def)*
apply *(simp add: Always_Int_I Un_commute)*
done

lemma *Detects_Always:*
"[|F ∈ A Detects B; all_total F|] ==> F ∈ Always (-(FP F) ∪ (A <==> B))"
apply *(unfold Detects_def Equality_def)*
apply *(simp add: Un_Int_distrib Always_Int_distrib)*
apply *(blast dest: Always_at_FP intro: Always_weaken)*
done

lemma *Detects_Imp_LeadstoEQ:*
"F ∈ A Detects B ==> F ∈ UNIV LeadsTo (A <==> B)"
apply *(unfold Detects_def Equality_def)*
apply *(rule_tac B = B* **in** *LeadsTo_Diff)*
apply *(blast intro: Always_LeadsToI subset_imp_LeadsTo)*
apply *(blast intro: Always_LeadsTo_weaken)*
done

end

7 Unions of Programs

theory *Union* **imports** *SubstAx FP* **begin**

definition
ok :: "['a program, 'a program] => bool" (**infixl** *"ok" 65)*
where *"F ok G == Acts F ⊆ AllowedActs G &*
Acts G ⊆ AllowedActs F"

definition
OK :: "['a set, 'a => 'b program] => bool"
where *"OK I F = (∀i ∈ I. ∀j ∈ I-{i}. Acts (F i) ⊆ AllowedActs (F j))"*

definition

JOIN :: "['a set, 'a => 'b program] => 'b program"
where *"JOIN I F = mk_program (⋂i ∈ I. Init (F i), ⋃i ∈ I. Acts (F i), ⋂i ∈ I. AllowedActs (F i))"*

definition
Join :: "['a program, 'a program] => 'a program" (**infixl** *"⊔" 65*)
where *"F ⊔ G = mk_program (Init F ∩ Init G, Acts F ∪ Acts G, AllowedActs F ∩ AllowedActs G)"*

definition *SKIP :: "'a program"* *("⊥")*
where *"⊥ = mk_program (UNIV, {}, UNIV)"*

definition
safety_prop :: "'a program set => bool"
where *"safety_prop X ⟷ SKIP ∈ X ∧ (∀G. Acts G ⊆ ⋃(Acts ‘ X) ⟶ G ∈ X)"*

syntax
"_JOIN1" :: "[pttrns, 'b set] => 'b set" *("(3⨆_./ _)" 10)*
"_JOIN" :: "[pttrn, 'a set, 'b set] => 'b set" *("(3⨆_∈_./ _)" 10)*
translations
"⨆x ∈ A. B" == "CONST JOIN A (λx. B)"
"⨆x y. B" == "⨆x. ⨆y. B"
"⨆x. B" == "CONST JOIN (CONST UNIV) (λx. B)"

7.1 SKIP

lemma *Init_SKIP [simp]: "Init SKIP = UNIV"*
by *(simp add: SKIP_def)*

lemma *Acts_SKIP [simp]: "Acts SKIP = {Id}"*
by *(simp add: SKIP_def)*

lemma *AllowedActs_SKIP [simp]: "AllowedActs SKIP = UNIV"*
by *(auto simp add: SKIP_def)*

lemma *reachable_SKIP [simp]: "reachable SKIP = UNIV"*
by *(force elim: reachable.induct intro: reachable.intros)*

7.2 SKIP and safety properties

lemma *SKIP_in_constrains_iff [iff]: "(SKIP ∈ A co B) = (A ⊆ B)"*
by *(unfold constrains_def, auto)*

lemma *SKIP_in_Constrains_iff [iff]: "(SKIP ∈ A Co B) = (A ⊆ B)"*
by *(unfold Constrains_def, auto)*

lemma *SKIP_in_stable [iff]: "SKIP ∈ stable A"*
by *(unfold stable_def, auto)*

declare *SKIP_in_stable [THEN stable_imp_Stable, iff]*

7.3 Join

lemma *Init_Join [simp]: "Init (F⊔G) = Init F ∩ Init G"*
by *(simp add: Join_def)*

lemma *Acts_Join [simp]: "Acts (F⊔G) = Acts F ∪ Acts G"*
by *(auto simp add: Join_def)*

lemma *AllowedActs_Join [simp]:*
"AllowedActs (F⊔G) = AllowedActs F ∩ AllowedActs G"
by *(auto simp add: Join_def)*

7.4 JN

lemma *JN_empty [simp]: "(⨆i∈{}. F i) = SKIP"*
by *(unfold JOIN_def SKIP_def, auto)*

lemma *JN_insert [simp]: "(⨆i ∈ insert a I. F i) = (F a)⊔(⨆i ∈ I. F i)"*
apply *(rule program_equalityI)*
apply *(auto simp add: JOIN_def Join_def)*
done

lemma *Init_JN [simp]: "Init (⨆i ∈ I. F i) = (⋂i ∈ I. Init (F i))"*
by *(simp add: JOIN_def)*

lemma *Acts_JN [simp]: "Acts (⨆i ∈ I. F i) = insert Id (⋃i ∈ I. Acts (F i))"*
by *(auto simp add: JOIN_def)*

lemma *AllowedActs_JN [simp]:*
"AllowedActs (⨆i ∈ I. F i) = (⋂i ∈ I. AllowedActs (F i))"
by *(auto simp add: JOIN_def)*

lemma *JN_cong [cong]:*
"[| I=J; !!i. i ∈ J ==> F i = G i |] ==> (⨆i ∈ I. F i) = (⨆i ∈ J. G i)"
by *(simp add: JOIN_def)*

7.5 Algebraic laws

lemma *Join_commute: "F⊔G = G⊔F"*
by *(simp add: Join_def Un_commute Int_commute)*

lemma *Join_assoc: "(F⊔G)⊔H = F⊔(G⊔H)"*
by *(simp add: Un_ac Join_def Int_assoc insert_absorb)*

lemma *Join_left_commute: "A⊔(B⊔C) = B⊔(A⊔C)"*
by *(simp add: Un_ac Int_ac Join_def insert_absorb)*

lemma *Join_SKIP_left [simp]: "SKIP⊔F = F"*
apply *(unfold Join_def SKIP_def)*
apply *(rule program_equalityI)*
apply *(simp_all (no_asm) add: insert_absorb)*
done

lemma *Join_SKIP_right [simp]: "F⊔SKIP = F"*
apply *(unfold Join_def SKIP_def)*
apply *(rule program_equalityI)*
apply *(simp_all (no_asm) add: insert_absorb)*
done

lemma *Join_absorb [simp]: "F⊔F = F"*
apply *(unfold Join_def)*
apply *(rule program_equalityI, auto)*
done

lemma *Join_left_absorb: "F⊔(F⊔G) = F⊔G"*
apply *(unfold Join_def)*
apply *(rule program_equalityI, auto)*
done

lemmas *Join_ac = Join_assoc Join_left_absorb Join_commute Join_left_commute*

7.6 Laws Governing ⨆

lemma *JN_absorb: "k ∈ I ==> F k⊔(⨆i ∈ I. F i) = (⨆i ∈ I. F i)"*
by *(auto intro!: program_equalityI)*

lemma *JN_Un: "(⨆i ∈ I ∪ J. F i) = ((⨆i ∈ I. F i)⊔(⨆i ∈ J. F i))"*
by *(auto intro!: program_equalityI)*

lemma *JN_constant: "(⨆i ∈ I. c) = (if I={} then SKIP else c)"*
by *(rule program_equalityI, auto)*

lemma *JN_Join_distrib:*
"(⨆i ∈ I. F i⊔G i) = (⨆i ∈ I. F i) ⊔ (⨆i ∈ I. G i)"
by *(auto intro!: program_equalityI)*

lemma *JN_Join_miniscope:*
"i ∈ I ==> (⨆i ∈ I. F i⊔G) = ((⨆i ∈ I. F i)⊔G)"
by *(auto simp add: JN_Join_distrib JN_constant)*

lemma *JN_Join_diff: "i ∈ I ==> F i⊔JOIN (I - {i}) F = JOIN I F"*
apply *(unfold JOIN_def Join_def)*
apply *(rule program_equalityI, auto)*
done

7.7 Safety: co, stable, FP

lemma *JN_constrains:*
"i ∈ I ==> (⨆i ∈ I. F i) ∈ A co B = (∀i ∈ I. F i ∈ A co B)"
by *(simp add: constrains_def JOIN_def, blast)*

lemma *Join_constrains [simp]:*
"(F⊔G ∈ A co B) = (F ∈ A co B & G ∈ A co B)"
by *(auto simp add: constrains_def Join_def)*

lemma *Join_unless [simp]:*
```
"(F⊔G ∈ A unless B) = (F ∈ A unless B & G ∈ A unless B)"
```
by *(simp add: unless_def)*

lemma *Join_constrains_weaken:*
```
"[| F ∈ A co A';  G ∈ B co B' |]
 ==> F⊔G ∈ (A ∩ B) co (A' ∪ B')"
```
by *(simp, blast intro: constrains_weaken)*

lemma *JN_constrains_weaken:*
```
"[| ∀i ∈ I. F i ∈ A i co A' i;  i ∈ I |]
 ==> (⨆i ∈ I. F i) ∈ (⋂i ∈ I. A i) co (⋃i ∈ I. A' i)"
```
apply *(simp (no_asm_simp) add: JN_constrains)*
apply *(blast intro: constrains_weaken)*
done

lemma *JN_stable:* $\text{"}(\bigsqcup i \in I.\ F\ i) \in \text{stable}\ A = (\forall i \in I.\ F\ i \in \text{stable}\ A)\text{"}$
by *(simp add: stable_def constrains_def JOIN_def)*

lemma *invariant_JN_I:*
```
"[| !!i. i ∈ I ==> F i ∈ invariant A;  i ∈ I |]
  ==> (⨆i ∈ I. F i) ∈ invariant A"
```
by *(simp add: invariant_def JN_stable, blast)*

lemma *Join_stable [simp]:*
```
"(F⊔G ∈ stable A) =
 (F ∈ stable A & G ∈ stable A)"
```
by *(simp add: stable_def)*

lemma *Join_increasing [simp]:*
```
"(F⊔G ∈ increasing f) =
 (F ∈ increasing f & G ∈ increasing f)"
```
by *(auto simp add: increasing_def)*

lemma *invariant_JoinI:*
```
"[| F ∈ invariant A; G ∈ invariant A |]
 ==> F⊔G ∈ invariant A"
```
by *(auto simp add: invariant_def)*

lemma *FP_JN:* $\text{"FP}\ (\bigsqcup i \in I.\ F\ i) = (\bigcap i \in I.\ \text{FP}\ (F\ i))\text{"}$
by *(simp add: FP_def JN_stable INTER_eq)*

7.8 Progress: transient, ensures

lemma *JN_transient:*
```
"i ∈ I ==>
(⨆i ∈ I. F i) ∈ transient A = (∃i ∈ I. F i ∈ transient A)"
```
by *(auto simp add: transient_def JOIN_def)*

lemma *Join_transient [simp]:*
```
     "F⊔G ∈ transient A =
      (F ∈ transient A | G ∈ transient A)"
```
by *(auto simp add: bex_Un transient_def Join_def)*

lemma *Join_transient_I1: "F ∈ transient A ==> F⊔G ∈ transient A"*
by *simp*

lemma *Join_transient_I2: "G ∈ transient A ==> F⊔G ∈ transient A"*
by *simp*

lemma *JN_ensures:*
```
     "i ∈ I ==>
      (⨆i ∈ I. F i) ∈ A ensures B =
      ((∀i ∈ I. F i ∈ (A-B) co (A ∪ B)) & (∃i ∈ I. F i ∈ A ensures B))"
```
by *(auto simp add: ensures_def JN_constrains JN_transient)*

lemma *Join_ensures:*
```
     "F⊔G ∈ A ensures B =
      (F ∈ (A-B) co (A ∪ B) & G ∈ (A-B) co (A ∪ B) &
       (F ∈ transient (A-B) | G ∈ transient (A-B)))"
```
by *(auto simp add: ensures_def)*

lemma *stable_Join_constrains:*
```
    "[| F ∈ stable A;  G ∈ A co A' |]
     ==> F⊔G ∈ A co A'"
```
apply *(unfold stable_def constrains_def Join_def)*
apply *(simp add: ball_Un, blast)*
done

lemma *stable_Join_Always1:*
```
     "[| F ∈ stable A;  G ∈ invariant A |] ==> F⊔G ∈ Always A"
```
apply *(simp (no_asm_use) add: Always_def invariant_def Stable_eq_stable)*
apply *(force intro: stable_Int)*
done

lemma *stable_Join_Always2:*
```
     "[| F ∈ invariant A;  G ∈ stable A |] ==> F⊔G ∈ Always A"
```
apply *(subst Join_commute)*
apply *(blast intro: stable_Join_Always1)*
done

lemma *stable_Join_ensures1:*
```
     "[| F ∈ stable A;  G ∈ A ensures B |] ==> F⊔G ∈ A ensures B"
```
apply *(simp (no_asm_simp) add: Join_ensures)*
apply *(simp add: stable_def ensures_def)*
apply *(erule constrains_weaken, auto)*
done

lemma *stable_Join_ensures2:*

```
    "[| F ∈ A ensures B;  G ∈ stable A |] ==> F⊔G ∈ A ensures B"
apply (subst Join_commute)
apply (blast intro: stable_Join_ensures1)
done
```

7.9 the ok and OK relations

```
lemma ok_SKIP1 [iff]: "SKIP ok F"
by (simp add: ok_def)

lemma ok_SKIP2 [iff]: "F ok SKIP"
by (simp add: ok_def)

lemma ok_Join_commute:
    "(F ok G & (F⊔G) ok H) = (G ok H & F ok (G⊔H))"
by (auto simp add: ok_def)

lemma ok_commute: "(F ok G) = (G ok F)"
by (auto simp add: ok_def)

lemmas ok_sym = ok_commute [THEN iffD1]

lemma ok_iff_OK:
    "OK {(0::int,F),(1,G),(2,H)} snd = (F ok G & (F⊔G) ok H)"
apply (simp add: Ball_def conj_disj_distribR ok_def Join_def OK_def insert_absorb
            all_conj_distrib)
apply blast
done

lemma ok_Join_iff1 [iff]: "F ok (G⊔H) = (F ok G & F ok H)"
by (auto simp add: ok_def)

lemma ok_Join_iff2 [iff]: "(G⊔H) ok F = (G ok F & H ok F)"
by (auto simp add: ok_def)


lemma ok_Join_commute_I: "[| F ok G; (F⊔G) ok H |] ==> F ok (G⊔H)"
by (auto simp add: ok_def)

lemma ok_JN_iff1 [iff]: "F ok (JOIN I G) = (∀i ∈ I. F ok G i)"
by (auto simp add: ok_def)

lemma ok_JN_iff2 [iff]: "(JOIN I G) ok F =  (∀i ∈ I. G i ok F)"
by (auto simp add: ok_def)

lemma OK_iff_ok: "OK I F = (∀i ∈ I. ∀j ∈ I-{i}. (F i) ok (F j))"
by (auto simp add: ok_def OK_def)

lemma OK_imp_ok: "[| OK I F; i ∈ I; j ∈ I; i ≠ j|] ==> (F i) ok (F j)"
by (auto simp add: OK_iff_ok)
```

7.10 Allowed

```
lemma Allowed_SKIP [simp]: "Allowed SKIP = UNIV"
```

by *(auto simp add: Allowed_def)*

lemma *Allowed_Join [simp]: "Allowed (F⊔G) = Allowed F ∩ Allowed G"*
by *(auto simp add: Allowed_def)*

lemma *Allowed_JN [simp]: "Allowed (JOIN I F) = (⋂i ∈ I. Allowed (F i))"*
by *(auto simp add: Allowed_def)*

lemma *ok_iff_Allowed: "F ok G = (F ∈ Allowed G & G ∈ Allowed F)"*
by *(simp add: ok_def Allowed_def)*

lemma *OK_iff_Allowed: "OK I F = (∀i ∈ I. ∀j ∈ I-{i}. F i ∈ Allowed(F j))"*
by *(auto simp add: OK_iff_ok ok_iff_Allowed)*

7.11 *safety_prop*, for reasoning about given instances of "ok"

lemma *safety_prop_Acts_iff:*
"safety_prop X ==> (Acts G ⊆ insert Id (⋃(Acts ‘ X))) = (G ∈ X)"
by *(auto simp add: safety_prop_def)*

lemma *safety_prop_AllowedActs_iff_Allowed:*
"safety_prop X ==> (⋃(Acts ‘ X) ⊆ AllowedActs F) = (X ⊆ Allowed F)"
by *(auto simp add: Allowed_def safety_prop_Acts_iff [symmetric])*

lemma *Allowed_eq:*
"safety_prop X ==> Allowed (mk_program (init, acts, ⋃(Acts ‘ X))) = X"
by *(simp add: Allowed_def safety_prop_Acts_iff)*

lemma *safety_prop_constrains [iff]: "safety_prop (A co B) = (A ⊆ B)"*
by *(simp add: safety_prop_def constrains_def, blast)*

lemma *safety_prop_stable [iff]: "safety_prop (stable A)"*
by *(simp add: stable_def)*

lemma *safety_prop_Int [simp]:*
"safety_prop X ⟹ safety_prop Y ⟹ safety_prop (X ∩ Y)"
proof *(clarsimp simp add: safety_prop_def)*
fix *G*
assume *"∀G. Acts G ⊆ (⋃x∈X. Acts x) ⟶ G ∈ X"*
then have *X: "Acts G ⊆ (⋃x∈X. Acts x) ⟹ G ∈ X"* **by** *blast*
assume *"∀G. Acts G ⊆ (⋃x∈Y. Acts x) ⟶ G ∈ Y"*
then have *Y: "Acts G ⊆ (⋃x∈Y. Acts x) ⟹ G ∈ Y"* **by** *blast*
assume *Acts: "Acts G ⊆ (⋃x∈X ∩ Y. Acts x)"*
with *X* **and** *Y* **show** *"G ∈ X ∧ G ∈ Y"* **by** *auto*
qed

lemma *safety_prop_INTER [simp]:*
"(⋀i. i ∈ I ⟹ safety_prop (X i)) ⟹ safety_prop (⋂i∈I. X i)"
proof *(clarsimp simp add: safety_prop_def)*
fix *G* **and** *i*
assume *"⋀i. i ∈ I ⟹ ⊥ ∈ X i ∧*
(∀G. Acts G ⊆ (⋃x∈X i. Acts x) ⟶ G ∈ X i)"

```
  then have *: "i ∈ I ⟹ Acts G ⊆ (⋃x∈X i. Acts x) ⟹ G ∈ X i"
    by blast
  assume "i ∈ I"
  moreover assume "Acts G ⊆ (⋃j∈⋂i∈I. X i. Acts j)"
  ultimately have "Acts G ⊆ (⋃i∈X i. Acts i)"
    by auto
  with * ‹i ∈ I› show "G ∈ X i" by blast
qed

lemma safety_prop_INTER1 [simp]:
  "(⋀i. safety_prop (X i)) ⟹ safety_prop (⋂i. X i)"
  by (rule safety_prop_INTER) simp

lemma def_prg_Allowed:
     "[| F == mk_program (init, acts, ⋃(Acts ‘ X)) ; safety_prop X |]
      ==> Allowed F = X"
by (simp add: Allowed_eq)

lemma Allowed_totalize [simp]: "Allowed (totalize F) = Allowed F"
by (simp add: Allowed_def)

lemma def_total_prg_Allowed:
     "[| F = mk_total_program (init, acts, ⋃(Acts ‘ X)) ; safety_prop X |]

      ==> Allowed F = X"
by (simp add: mk_total_program_def def_prg_Allowed)

lemma def_UNION_ok_iff:
     "[| F = mk_program(init,acts,⋃(Acts ‘ X)); safety_prop X |]
      ==> F ok G = (G ∈ X & acts ⊆ AllowedActs G)"
by (auto simp add: ok_def safety_prop_Acts_iff)
```

The union of two total programs is total.

```
lemma totalize_Join: "totalize F⊔totalize G = totalize (F⊔G)"
by (simp add: program_equalityI totalize_def Join_def image_Un)

lemma all_total_Join: "[|all_total F; all_total G|] ==> all_total (F⊔G)"
by (simp add: all_total_def, blast)

lemma totalize_JN: "(⨆i ∈ I. totalize (F i)) = totalize(⨆i ∈ I. F i)"
by (simp add: program_equalityI totalize_def JOIN_def image_UN)

lemma all_total_JN: "(!!i. i∈I ==> all_total (F i)) ==> all_total(⨆i∈I.
F i)"
by (simp add: all_total_iff_totalize totalize_JN [symmetric])

end
```

8 Composition: Basic Primitives

```
theory Comp
imports Union
begin
```

instantiation *program :: (type) ord*
begin

definition *component_def: "F ≤ H ⟷ (∃G. F⊔G = H)"*

definition *strict_component_def: "F < (H::'a program) ⟷ (F ≤ H & F ≠ H)"*

instance ..

end

definition *component_of :: "'a program =>'a program=> bool"* (**infixl** *"component'_of" 50)*
  where *"F component_of H == ∃G. F ok G & F⊔G = H"*

definition *strict_component_of :: "'a program⇒'a program=> bool"* (**infixl** *"strict'_component'_of" 50)*
  where *"F strict_component_of H == F component_of H & F≠H"*

definition *preserves :: "('a=>'b) => 'a program set"*
  where *"preserves v == ⋂z. stable {s. v s = z}"*

definition *localize :: "('a=>'b) => 'a program => 'a program"* **where**
  "localize v F == mk_program(Init F, Acts F,
AllowedActs F ∩ (⋃G ∈ preserves v. Acts G))"

definition *funPair :: "['a => 'b, 'a => 'c, 'a] => 'b * 'c"*
  where *"funPair f g == %x. (f x, g x)"*

8.1 The component relation

lemma *componentI: "H ≤ F | H ≤ G ==> H ≤ (F⊔G)"*
apply *(unfold component_def, auto)*
apply *(rule_tac x = "G⊔Ga"* **in** *exI)*
apply *(rule_tac [2] x = "G⊔F"* **in** *exI)*
apply *(auto simp add: Join_ac)*
done

lemma *component_eq_subset:*
"(F ≤ G) =
(Init G ⊆ Init F & Acts F ⊆ Acts G & AllowedActs G ⊆ AllowedActs F)"
apply *(unfold component_def)*
apply *(force intro!: exI program_equalityI)*
done

lemma *component_SKIP [iff]: "SKIP ≤ F"*
apply *(unfold component_def)*
apply *(force intro: Join_SKIP_left)*
done

lemma *component_refl [iff]: "F ≤ (F :: 'a program)"*
apply *(unfold component_def)*
apply *(blast intro: Join_SKIP_right)*

done

lemma *SKIP_minimal: "F ≤ SKIP ==> F = SKIP"*
by *(auto intro!: program_equalityI simp add: component_eq_subset)*

lemma *component_Join1: "F ≤ (F⊔G)"*
by *(unfold component_def, blast)*

lemma *component_Join2: "G ≤ (F⊔G)"*
apply *(unfold component_def)*
apply *(simp add: Join_commute, blast)*
done

lemma *Join_absorb1: "F ≤ G ==> F⊔G = G"*
by *(auto simp add: component_def Join_left_absorb)*

lemma *Join_absorb2: "G ≤ F ==> F⊔G = F"*
by *(auto simp add: Join_ac component_def)*

lemma *JN_component_iff: "((JOIN I F) ≤ H) = (∀i ∈ I. F i ≤ H)"*
by *(simp add: component_eq_subset, blast)*

lemma *component_JN: "i ∈ I ==> (F i) ≤ (⨆i ∈ I. (F i))"*
apply *(unfold component_def)*
apply *(blast intro: JN_absorb)*
done

lemma *component_trans: "[| F ≤ G; G ≤ H |] ==> F ≤ (H :: 'a program)"*
apply *(unfold component_def)*
apply *(blast intro: Join_assoc [symmetric])*
done

lemma *component_antisym: "[| F ≤ G; G ≤ F |] ==> F = (G :: 'a program)"*
apply *(simp (no_asm_use) add: component_eq_subset)*
apply *(blast intro!: program_equalityI)*
done

lemma *Join_component_iff: "((F⊔G) ≤ H) = (F ≤ H & G ≤ H)"*
by *(simp add: component_eq_subset, blast)*

lemma *component_constrains: "[| F ≤ G; G ∈ A co B |] ==> F ∈ A co B"*
by *(auto simp add: constrains_def component_eq_subset)*

lemma *component_stable: "[| F ≤ G; G ∈ stable A |] ==> F ∈ stable A"*
by *(auto simp add: stable_def component_constrains)*

lemmas *program_less_le = strict_component_def*

8.2 The preserves property

lemma *preservesI: "(!!z. F ∈ stable {s. v s = z}) ==> F ∈ preserves v"*
by *(unfold preserves_def, blast)*

lemma *preserves_imp_eq:*
"[| F ∈ preserves v; act ∈ Acts F; (s,s') ∈ act |] ==> v s = v s'"
by (unfold preserves_def stable_def constrains_def, force)

lemma *Join_preserves [iff]:*
"(F⊔G ∈ preserves v) = (F ∈ preserves v & G ∈ preserves v)"
by (unfold preserves_def, auto)

lemma *JN_preserves [iff]:*
"(JOIN I F ∈ preserves v) = (∀i ∈ I. F i ∈ preserves v)"
by (simp add: JN_stable preserves_def, blast)

lemma *SKIP_preserves [iff]: "SKIP ∈ preserves v"*
by (auto simp add: preserves_def)

lemma *funPair_apply [simp]: "(funPair f g) x = (f x, g x)"*
by (simp add: funPair_def)

lemma *preserves_funPair: "preserves (funPair v w) = preserves v ∩ preserves w"*
by (auto simp add: preserves_def stable_def constrains_def, blast)

declare *preserves_funPair [THEN eqset_imp_iff, iff]*

lemma *funPair_o_distrib: "(funPair f g) o h = funPair (f o h) (g o h)"*
by (simp add: funPair_def o_def)

lemma *fst_o_funPair [simp]: "fst o (funPair f g) = f"*
by (simp add: funPair_def o_def)

lemma *snd_o_funPair [simp]: "snd o (funPair f g) = g"*
by (simp add: funPair_def o_def)

lemma *subset_preserves_o: "preserves v ⊆ preserves (w o v)"*
by (force simp add: preserves_def stable_def constrains_def)

lemma *preserves_subset_stable: "preserves v ⊆ stable {s. P (v s)}"*
apply (auto simp add: preserves_def stable_def constrains_def)
apply (rename_tac s' s)
apply (subgoal_tac "v s = v s'")
apply (force+)
done

lemma *preserves_subset_increasing: "preserves v ⊆ increasing v"*
by (auto simp add: preserves_subset_stable [THEN subsetD] increasing_def)

lemma *preserves_id_subset_stable: "preserves id ⊆ stable A"*
by (force simp add: preserves_def stable_def constrains_def)

```
lemma safety_prop_preserves [iff]: "safety_prop (preserves v)"
by (auto intro: safety_prop_INTER1 simp add: preserves_def)



lemma stable_localTo_stable2:
     "[| F ∈ stable {s. P (v s) (w s)};
         G ∈ preserves v;  G ∈ preserves w |]
      ==> F⊔G ∈ stable {s. P (v s) (w s)}"
apply simp
apply (subgoal_tac "G ∈ preserves (funPair v w) ")
 prefer 2 apply simp
apply (drule_tac P1 = "case_prod Q" for Q in preserves_subset_stable [THEN
subsetD],
       auto)
done

lemma Increasing_preserves_Stable:
     "[| F ∈ stable {s. v s ≤ w s};  G ∈ preserves v; F⊔G ∈ Increasing w
|]
      ==> F⊔G ∈ Stable {s. v s ≤ w s}"
apply (auto simp add: stable_def Stable_def Increasing_def Constrains_def
all_conj_distrib)
apply (blast intro: constrains_weaken)

apply (auto simp add: preserves_def stable_def constrains_def)

apply (erule_tac V = "∀act ∈ Acts F. P act" for P in thin_rl)
apply (erule_tac V = "∀z. ∀act ∈ Acts F. P z act" for P in thin_rl)
apply (subgoal_tac "v x = v xa")
 apply auto
apply (erule order_trans, blast)
done



lemma component_of_imp_component: "F component_of H ==> F ≤ H"
by (unfold component_def component_of_def, blast)



lemma component_of_refl [simp]: "F component_of F"
apply (unfold component_of_def)
apply (rule_tac x = SKIP in exI, auto)
done

lemma component_of_SKIP [simp]: "SKIP component_of F"
by (unfold component_of_def, auto)

lemma component_of_trans:
     "[| F component_of G; G component_of H |] ==> F component_of H"
apply (unfold component_of_def)
```

apply *(blast intro: Join_assoc [symmetric])*
done

lemmas *strict_component_of_eq = strict_component_of_def*

lemma *localize_Init_eq [simp]: "Init (localize v F) = Init F"*
by *(simp add: localize_def)*

lemma *localize_Acts_eq [simp]: "Acts (localize v F) = Acts F"*
by *(simp add: localize_def)*

lemma *localize_AllowedActs_eq [simp]:*
"AllowedActs (localize v F) = AllowedActs F ∩ (⋃G ∈ preserves v. Acts G)"
by *(unfold localize_def, auto)*

end

9 Guarantees Specifications

theory *Guar*
imports *Comp*
begin

instance *program :: (type) order*
by *standard (auto simp add: program_less_le dest: component_antisym intro: component_trans)*

Existential and Universal properties. I formalize the two-program case, proving equivalence with Chandy and Sanders's n-ary definitions

definition *ex_prop :: "'a program set => bool"* **where**
"ex_prop X == ∀F G. F ok G -->F ∈ X | G ∈ X --> (F⊔G) ∈ X"

definition *strict_ex_prop :: "'a program set => bool"* **where**
"strict_ex_prop X == ∀F G. F ok G --> (F ∈ X | G ∈ X) = (F⊔G ∈ X)"

definition *uv_prop :: "'a program set => bool"* **where**
"uv_prop X == SKIP ∈ X & (∀F G. F ok G --> F ∈ X & G ∈ X --> (F⊔G) ∈ X)"

definition *strict_uv_prop :: "'a program set => bool"* **where**
"strict_uv_prop X ==
SKIP ∈ X & (∀F G. F ok G --> (F ∈ X & G ∈ X) = (F⊔G ∈ X))"

Guarantees properties

definition *guar :: "['a program set, 'a program set] => 'a program set"* (**infixl** *"guarantees" 55)* **where**

"X guarantees Y == {F. ∀G. F ok G --> F⊔G ∈ X --> F⊔G ∈ Y}"

definition *wg :: "['a program, 'a program set] => 'a program set"* **where**
"wg F Y == ⋃({X. F ∈ X guarantees Y})"

definition *wx :: "('a program) set => ('a program)set"* **where**
"wx X == ⋃({Y. Y ⊆ X & ex_prop Y})"

definition *welldef :: "'a program set"* **where**
"welldef == {F. Init F ≠ {}}"

definition *refines :: "['a program, 'a program, 'a program set] => bool"*
("(3_ refines _ wrt _)" [10,10,10] 10) **where**
"G refines F wrt X ==
∀H. (F ok H & G ok H & F⊔H ∈ welldef ∩ X) -->
(G⊔H ∈ welldef ∩ X)"

definition *iso_refines :: "['a program, 'a program, 'a program set] => bool"*
("(3_ iso'_refines _ wrt _)" [10,10,10] 10) **where**
"G iso_refines F wrt X ==
F ∈ welldef ∩ X --> G ∈ welldef ∩ X"

lemma *OK_insert_iff:*
"(OK (insert i I) F) =
(if i ∈ I then OK I F else OK I F & (F i ok JOIN I F))"
by *(auto intro: ok_sym simp add: OK_iff_ok)*

9.1 Existential Properties

lemma *ex1:*
assumes *"ex_prop X"* **and** *"finite GG"*
shows *"GG ∩ X ≠ {} ⟹ OK GG (%G. G) ⟹ (⨆G ∈ GG. G) ∈ X"*
apply *(atomize (full))*
using *assms(2)* **apply** *induct*
using *assms(1)* **apply** *(unfold ex_prop_def)*
apply *(auto simp add: OK_insert_iff Int_insert_left)*
done

lemma *ex2:*
"∀GG. finite GG & GG ∩ X ≠ {} ⟶ OK GG (λG. G) ⟶ (⨆G ∈ GG. G) ∈ X
⟹ ex_prop X"
apply *(unfold ex_prop_def, clarify)*
apply *(drule_tac x = "{F,G}"* **in** *spec)*
apply *(auto dest: ok_sym simp add: OK_iff_ok)*
done

lemma *ex_prop_finite:*
"ex_prop X =
(∀GG. finite GG & GG ∩ X ≠ {} & OK GG (%G. G)--> (⨆G ∈ GG. G) ∈ X)"
by *(blast intro: ex1 ex2)*

```
lemma ex_prop_equiv:
     "ex_prop X = (∀G. G ∈ X = (∀H. (G component_of H) --> H ∈ X))"
apply auto
apply (unfold ex_prop_def component_of_def, safe, blast, blast)
apply (subst Join_commute)
apply (drule ok_sym, blast)
done
```

9.2 Universal Properties

```
lemma uv1:
  assumes "uv_prop X"
    and "finite GG"
    and "GG ⊆ X"
    and "OK GG (%G. G)"
  shows "(⨆G ∈ GG. G) ∈ X"
  using assms(2-)
  apply induct
   using assms(1)
   apply (unfold uv_prop_def)
   apply (auto simp add: Int_insert_left OK_insert_iff)
  done

lemma uv2:
     "∀GG. finite GG & GG ⊆ X & OK GG (%G. G) --> (⨆G ∈ GG. G) ∈ X
      ==> uv_prop X"
apply (unfold uv_prop_def)
apply (rule conjI)
 apply (drule_tac x = "{}" in spec)
 prefer 2
 apply clarify
 apply (drule_tac x = "{F,G}" in spec)
apply (auto dest: ok_sym simp add: OK_iff_ok)
done


lemma uv_prop_finite:
     "uv_prop X =
      (∀GG. finite GG ∧ GG ⊆ X ∧ OK GG (λG. G) ⟶ (⨆G ∈ GG. G) ∈ X)"
by (blast intro: uv1 uv2)
```

9.3 Guarantees

```
lemma guaranteesI:
     "(!!G. [| F ok G; F⊔G ∈ X |] ==> F⊔G ∈ Y) ==> F ∈ X guarantees Y"
by (simp add: guar_def component_def)

lemma guaranteesD:
     "[| F ∈ X guarantees Y;  F ok G;  F⊔G ∈ X |] ==> F⊔G ∈ Y"
by (unfold guar_def component_def, blast)
```

lemma *component_guaranteesD:*
"[| F ∈ X guarantees Y; F⨆G = H; H ∈ X; F ok G |] ==> H ∈ Y"
by *(unfold guar_def, blast)*

lemma *guarantees_weaken:*
"[| F ∈ X guarantees X'; Y ⊆ X; X' ⊆ Y' |] ==> F ∈ Y guarantees Y'"
by *(unfold guar_def, blast)*

lemma *subset_imp_guarantees_UNIV: "X ⊆ Y ==> X guarantees Y = UNIV"*
by *(unfold guar_def, blast)*

lemma *subset_imp_guarantees: "X ⊆ Y ==> F ∈ X guarantees Y"*
by *(unfold guar_def, blast)*

lemma *ex_prop_imp: "ex_prop Y ==> (Y = UNIV guarantees Y)"*
apply *(simp (no_asm_use) add: guar_def ex_prop_equiv)*
apply *safe*
apply *(drule_tac x = x* **in** *spec)*
apply *(drule_tac [2] x = x* **in** *spec)*
apply *(drule_tac [2] sym)*
apply *(auto simp add: component_of_def)*
done

lemma *guarantees_imp: "(Y = UNIV guarantees Y) ==> ex_prop(Y)"*
by *(auto simp add: guar_def ex_prop_equiv component_of_def dest: sym)*

lemma *ex_prop_equiv2: "(ex_prop Y) = (Y = UNIV guarantees Y)"*
apply *(rule iffI)*
apply *(rule ex_prop_imp)*
apply *(auto simp add: guarantees_imp)*
done

9.4 Distributive Laws. Re-Orient to Perform Miniscoping

lemma *guarantees_UN_left:*
"(⋃ i ∈ I. X i) guarantees Y = (⋂ i ∈ I. X i guarantees Y)"
by *(unfold guar_def, blast)*

lemma *guarantees_Un_left:*
"(X ∪ Y) guarantees Z = (X guarantees Z) ∩ (Y guarantees Z)"
by *(unfold guar_def, blast)*

lemma *guarantees_INT_right:*
"X guarantees (⋂ i ∈ I. Y i) = (⋂ i ∈ I. X guarantees Y i)"
by *(unfold guar_def, blast)*

lemma *guarantees_Int_right:*
"Z guarantees (X ∩ Y) = (Z guarantees X) ∩ (Z guarantees Y)"
by *(unfold guar_def, blast)*

lemma *guarantees_Int_right_I:*
```
"[| F ∈ Z guarantees X;  F ∈ Z guarantees Y |]
 ==> F ∈ Z guarantees (X ∩ Y)"
```
by *(simp add: guarantees_Int_right)*

lemma *guarantees_INT_right_iff:*
```
"(F ∈ X guarantees (⋂(Y ` I))) = (∀i∈I. F ∈ X guarantees (Y i))"
```
by *(simp add: guarantees_INT_right)*

lemma *shunting:* `"(X guarantees Y) = (UNIV guarantees (-X ∪ Y))"`
by *(unfold guar_def, blast)*

lemma *contrapositive:* `"(X guarantees Y) = -Y guarantees -X"`
by *(unfold guar_def, blast)*

lemma *combining1:*
```
"[| F ∈ V guarantees X;  F ∈ (X ∩ Y) guarantees Z |]
 ==> F ∈ (V ∩ Y) guarantees Z"
```
by *(unfold guar_def, blast)*

lemma *combining2:*
```
"[| F ∈ V guarantees (X ∪ Y);  F ∈ Y guarantees Z |]
 ==> F ∈ V guarantees (X ∪ Z)"
```
by *(unfold guar_def, blast)*

lemma *all_guarantees:*
```
"∀i∈I. F ∈ X guarantees (Y i) ==> F ∈ X guarantees (⋂i ∈ I. Y i)"
```
by *(unfold guar_def, blast)*

lemma *ex_guarantees:*
```
"∃i∈I. F ∈ X guarantees (Y i) ==> F ∈ X guarantees (⋃i ∈ I. Y i)"
```
by *(unfold guar_def, blast)*

9.5 Guarantees: Additional Laws (by lcp)

lemma *guarantees_Join_Int:*
```
"[| F ∈ U guarantees V;  G ∈ X guarantees Y; F ok G |]
 ==> F⊔G ∈ (U ∩ X) guarantees (V ∩ Y)"
```
apply *(simp add: guar_def, safe)*
apply *(simp add: Join_assoc)*
apply *(subgoal_tac "F⊔G⊔Ga = G⊔(F⊔Ga) ")*
apply *(simp add: ok_commute)*
apply *(simp add: Join_ac)*
done

lemma *guarantees_Join_Un:*
```
"[| F ∈ U guarantees V;  G ∈ X guarantees Y; F ok G |]
 ==> F⊔G ∈ (U ∪ X) guarantees (V ∪ Y)"
```

```
apply (simp add: guar_def, safe)
 apply (simp add: Join_assoc)
apply (subgoal_tac "F⊔G⊔Ga = G⊔(F⊔Ga) ")
 apply (simp add: ok_commute)
apply (simp add: Join_ac)
done

lemma guarantees_JN_INT:
     "[| ∀i∈I. F i ∈ X i guarantees Y i;  OK I F |]
      ==> (JOIN I F) ∈ (⋂(X ` I)) guarantees (⋂(Y ` I))"
apply (unfold guar_def, auto)
apply (drule bspec, assumption)
apply (rename_tac "i")
apply (drule_tac x = "JOIN (I-{i}) F⊔G" in spec)
apply (auto intro: OK_imp_ok
            simp add: Join_assoc [symmetric] JN_Join_diff JN_absorb)
done

lemma guarantees_JN_UN:
    "[| ∀i∈I. F i ∈ X i guarantees Y i;  OK I F |]
     ==> (JOIN I F) ∈ (⋃(X ` I)) guarantees (⋃(Y ` I))"
apply (unfold guar_def, auto)
apply (drule bspec, assumption)
apply (rename_tac "i")
apply (drule_tac x = "JOIN (I-{i}) F⊔G" in spec)
apply (auto intro: OK_imp_ok
            simp add: Join_assoc [symmetric] JN_Join_diff JN_absorb)
done
```

9.6 Guarantees Laws for Breaking Down the Program (by lcp)

```
lemma guarantees_Join_I1:
     "[| F ∈ X guarantees Y;  F ok G |] ==> F⊔G ∈ X guarantees Y"
by (simp add: guar_def Join_assoc)

lemma guarantees_Join_I2:
     "[| G ∈ X guarantees Y;  F ok G |] ==> F⊔G ∈ X guarantees Y"
apply (simp add: Join_commute [of _ G] ok_commute [of _ G])
apply (blast intro: guarantees_Join_I1)
done

lemma guarantees_JN_I:
     "[| i ∈ I;  F i ∈ X guarantees Y;  OK I F |]
      ==> (⨆i ∈ I. (F i)) ∈ X guarantees Y"
apply (unfold guar_def, clarify)
apply (drule_tac x = "JOIN (I-{i}) F⊔G" in spec)
apply (auto intro: OK_imp_ok simp add: JN_Join_diff Join_assoc [symmetric])
done



lemma Join_welldef_D1: "F⊔G ∈ welldef ==> F ∈ welldef"
```

```
by (unfold welldef_def, auto)

lemma Join_welldef_D2: "F⊔G ∈ welldef ==> G ∈ welldef"
by (unfold welldef_def, auto)



lemma refines_refl: "F refines F wrt X"
by (unfold refines_def, blast)


lemma refines_trans:
     "[| H refines G wrt X;  G refines F wrt X |] ==> H refines F wrt X"
apply (simp add: refines_def)
oops


lemma strict_ex_refine_lemma:
     "strict_ex_prop X
      ==> (∀H. F ok H & G ok H & F⊔H ∈ X --> G⊔H ∈ X)
              = (F ∈ X --> G ∈ X)"
by (unfold strict_ex_prop_def, auto)

lemma strict_ex_refine_lemma_v:
     "strict_ex_prop X
      ==> (∀H. F ok H & G ok H & F⊔H ∈ welldef & F⊔H ∈ X --> G⊔H ∈ X) =

          (F ∈ welldef ∩ X --> G ∈ X)"
apply (unfold strict_ex_prop_def, safe)
apply (erule_tac x = SKIP and P = "%H. PP H --> RR H" for PP RR in allE)
apply (auto dest: Join_welldef_D1 Join_welldef_D2)
done

lemma ex_refinement_thm:
     "[| strict_ex_prop X;
         ∀H. F ok H & G ok H & F⊔H ∈ welldef ∩ X --> G⊔H ∈ welldef |]
      ==> (G refines F wrt X) = (G iso_refines F wrt X)"
apply (rule_tac x = SKIP in allE, assumption)
apply (simp add: refines_def iso_refines_def strict_ex_refine_lemma_v)
done


lemma strict_uv_refine_lemma:
     "strict_uv_prop X ==>
      (∀H. F ok H & G ok H & F⊔H ∈ X --> G⊔H ∈ X) = (F ∈ X --> G ∈ X)"
by (unfold strict_uv_prop_def, blast)

lemma strict_uv_refine_lemma_v:
     "strict_uv_prop X
      ==> (∀H. F ok H & G ok H & F⊔H ∈ welldef & F⊔H ∈ X --> G⊔H ∈ X) =

          (F ∈ welldef ∩ X --> G ∈ X)"
apply (unfold strict_uv_prop_def, safe)
apply (erule_tac x = SKIP and P = "%H. PP H --> RR H" for PP RR in allE)
```

```
apply (auto dest: Join_welldef_D1 Join_welldef_D2)
done

lemma uv_refinement_thm:
     "[| strict_uv_prop X;
         ∀H. F ok H & G ok H & F⊔H ∈ welldef ∩ X -->
             G⊔H ∈ welldef |]
      ==> (G refines F wrt X) = (G iso_refines F wrt X)"
apply (rule_tac x = SKIP in allE, assumption)
apply (simp add: refines_def iso_refines_def strict_uv_refine_lemma_v)
done


lemma guarantees_equiv:
    "(F ∈ X guarantees Y) = (∀H. H ∈ X ⟶ (F component_of H ⟶ H ∈ Y))"
by (unfold guar_def component_of_def, auto)

lemma wg_weakest: "!!X. F∈ (X guarantees Y) ==> X ⊆ (wg F Y)"
by (unfold wg_def, auto)

lemma wg_guarantees: "F∈ ((wg F Y) guarantees Y)"
by (unfold wg_def guar_def, blast)

lemma wg_equiv: "(H ∈ wg F X) = (F component_of H --> H ∈ X)"
by (simp add: guarantees_equiv wg_def, blast)

lemma component_of_wg: "F component_of H ==> (H ∈ wg F X) = (H ∈ X)"
by (simp add: wg_equiv)

lemma wg_finite:
    "∀FF. finite FF ∧ FF ∩ X ≠ {} ⟶ OK FF (λF. F)
          ⟶ (∀F∈FF. ((⨆F ∈ FF. F) ∈ wg F X) = ((⨆F ∈ FF. F) ∈ X))"
apply clarify
apply (subgoal_tac "F component_of (⨆F ∈ FF. F) ")
apply (drule_tac X = X in component_of_wg, simp)
apply (simp add: component_of_def)
apply (rule_tac x = "⨆F ∈ (FF-{F}) . F" in exI)
apply (auto intro: JN_Join_diff dest: ok_sym simp add: OK_iff_ok)
done

lemma wg_ex_prop: "ex_prop X ==> (F ∈ X) = (∀H. H ∈ wg F X)"
apply (simp (no_asm_use) add: ex_prop_equiv wg_equiv)
apply blast
done



lemma wx_subset: "(wx X)<=X"
by (unfold wx_def, auto)

lemma wx_ex_prop: "ex_prop (wx X)"
apply (simp add: wx_def ex_prop_equiv cong: bex_cong, safe, blast)
apply force
done
```

```
lemma wx_weakest: "∀Z. Z<= X --> ex_prop Z --> Z ⊆ wx X"
by (auto simp add: wx_def)


lemma wx'_ex_prop: "ex_prop({F. ∀G. F ok G --> F⊔G ∈ X})"
apply (unfold ex_prop_def, safe)
 apply (drule_tac x = "G⊔Ga" in spec)
 apply (force simp add: Join_assoc)
apply (drule_tac x = "F⊔Ga" in spec)
apply (simp add: ok_commute  Join_ac)
done
```

Equivalence with the other definition of wx

```
lemma wx_equiv: "wx X = {F. ∀G. F ok G --> (F⊔G) ∈ X}"
apply (unfold wx_def, safe)
 apply (simp add: ex_prop_def, blast)
apply (simp (no_asm))
apply (rule_tac x = "{F. ∀G. F ok G --> F⊔G ∈ X}" in exI, safe)
apply (rule_tac [2] wx'_ex_prop)
apply (drule_tac x = SKIP in spec)+
apply auto
done
```

Propositions 7 to 11 are about this second definition of wx. They are the same as the ones proved for the first definition of wx, by equivalence

```
lemma guarantees_wx_eq: "(X guarantees Y) = wx(-X ∪ Y)"
by (simp add: guar_def wx_equiv)



lemma stable_guarantees_Always:
     "Init F ⊆ A ==> F ∈ (stable A) guarantees (Always A)"
apply (rule guaranteesI)
apply (simp add: Join_commute)
apply (rule stable_Join_Always1)
 apply (simp_all add: invariant_def)
done

lemma constrains_guarantees_leadsTo:
     "F ∈ transient A ==> F ∈ (A co A ∪ B) guarantees (A leadsTo (B-A))"
apply (rule guaranteesI)
apply (rule leadsTo_Basis')
 apply (drule constrains_weaken_R)
  prefer 2 apply assumption
 apply blast
apply (blast intro: Join_transient_I1)
done

end
```

10 Extending State Sets

theory *Extend* **imports** *Guar* **begin**

definition

```
  Restrict :: "[ 'a set, ('a*'b) set] => ('a*'b) set"
  where "Restrict A r = r ∩ (A × UNIV)"
```

definition

```
  good_map :: "['a*'b => 'c] => bool"
  where "good_map h ⟷ surj h & (∀x y. fst (inv h (h (x,y))) = x)"
```

definition

```
  extend_set :: "['a*'b => 'c, 'a set] => 'c set"
  where "extend_set h A = h ‘ (A × UNIV)"
```

definition

```
  project_set :: "['a*'b => 'c, 'c set] => 'a set"
  where "project_set h C = {x. ∃y. h(x,y) ∈ C}"
```

definition

```
  extend_act :: "['a*'b => 'c, ('a*'a) set] => ('c*'c) set"
  where "extend_act h = (%act. ⋃(s,s') ∈ act. ⋃y. {(h(s,y), h(s',y))})"
```

definition

```
  project_act :: "['a*'b => 'c, ('c*'c) set] => ('a*'a) set"
  where "project_act h act = {(x,x'). ∃y y'. (h(x,y), h(x',y')) ∈ act}"
```

definition

```
  extend :: "['a*'b => 'c, 'a program] => 'c program"
  where "extend h F = mk_program (extend_set h (Init F),
                                  extend_act h ‘ Acts F,
                                  project_act h -‘ AllowedActs F)"
```

definition

```
  project :: "['a*'b => 'c, 'c set, 'c program] => 'a program"
  where "project h C F =
       mk_program (project_set h (Init F),
                   project_act h ‘ Restrict C ‘ Acts F,
                   {act. Restrict (project_set h C) act ∈
                         project_act h ‘ Restrict C ‘ AllowedActs F})"
```

locale *Extend* =
  fixes *f* :: "'c => 'a"
    and *g* :: "'c => 'b"
    and *h* :: "'a*'b => 'c"
    and *slice* :: "['c set, 'b] => 'a set"
  assumes
    good_h: "good_map h"
  defines *f_def*: "f z == fst (inv h z)"
      and *g_def*: "g z == snd (inv h z)"

and *slice_def: "slice Z y == {x. h(x,y) ∈ Z}"*

10.1 Restrict

lemma *Restrict_iff [iff]: "((x,y) ∈ Restrict A r) = ((x,y) ∈ r & x ∈ A)"*
by *(unfold Restrict_def, blast)*

lemma *Restrict_UNIV [simp]: "Restrict UNIV = id"*
apply *(rule ext)*
apply *(auto simp add: Restrict_def)*
done

lemma *Restrict_empty [simp]: "Restrict {} r = {}"*
by *(auto simp add: Restrict_def)*

lemma *Restrict_Int [simp]: "Restrict A (Restrict B r) = Restrict (A ∩ B) r"*
by *(unfold Restrict_def, blast)*

lemma *Restrict_triv: "Domain r ⊆ A ==> Restrict A r = r"*
by *(unfold Restrict_def, auto)*

lemma *Restrict_subset: "Restrict A r ⊆ r"*
by *(unfold Restrict_def, auto)*

lemma *Restrict_eq_mono:*
"[| A ⊆ B; Restrict B r = Restrict B s |]
==> Restrict A r = Restrict A s"
by *(unfold Restrict_def, blast)*

lemma *Restrict_imageI:*
"[| s ∈ RR; Restrict A r = Restrict A s |]
==> Restrict A r ∈ Restrict A ‘ RR"
by *(unfold Restrict_def image_def, auto)*

lemma *Domain_Restrict [simp]: "Domain (Restrict A r) = A ∩ Domain r"*
by *blast*

lemma *Image_Restrict [simp]: "(Restrict A r) `` B = r `` (A ∩ B)"*
by *blast*

lemma *good_mapI:*
assumes *surj_h: "surj h"*
and *prem: "!! x x' y y'. h(x,y) = h(x',y') ==> x=x'"*
shows *"good_map h"*
apply *(simp add: good_map_def)*
apply *(safe intro!: surj_h)*
apply *(rule prem)*
apply *(subst surjective_pairing [symmetric])*
apply *(subst surj_h [THEN surj_f_inv_f])*
apply *(rule refl)*
done

```
lemma good_map_is_surj: "good_map h ==> surj h"
by (unfold good_map_def, auto)


lemma fst_inv_equalityI:
     assumes surj_h: "surj h"
         and prem:   "!! x y. g (h(x,y)) = x"
     shows "fst (inv h z) = g z"
by (metis UNIV_I f_inv_into_f prod.collapse prem surj_h)
```

10.2 Trivial properties of f, g, h

```
context Extend
begin

lemma f_h_eq [simp]: "f(h(x,y)) = x"
by (simp add: f_def good_h [unfolded good_map_def, THEN conjunct2])

lemma h_inject1 [dest]: "h(x,y) = h(x',y') ==> x=x'"
apply (drule_tac f = f in arg_cong)
apply (simp add: f_def good_h [unfolded good_map_def, THEN conjunct2])
done

lemma h_f_g_equiv: "h(f z, g z) == z"
by (simp add: f_def g_def
            good_h [unfolded good_map_def, THEN conjunct1, THEN surj_f_inv_f])

lemma h_f_g_eq: "h(f z, g z) = z"
by (simp add: h_f_g_equiv)


lemma split_extended_all:
     "(!!z. PROP P z) == (!!u y. PROP P (h (u, y)))"
proof
   assume allP: "⋀z. PROP P z"
   fix u y
   show "PROP P (h (u, y))" by (rule allP)
 next
   assume allPh: "⋀u y. PROP P (h(u,y))"
   fix z
   have Phfgz: "PROP P (h (f z, g z))" by (rule allPh)
   show "PROP P z" by (rule Phfgz [unfolded h_f_g_equiv])
qed

end
```

10.3 `extend_set`: basic properties

```
lemma project_set_iff [iff]:
     "(x ∈ project_set h C) = (∃y. h(x,y) ∈ C)"
by (simp add: project_set_def)

lemma extend_set_mono: "A ⊆ B ==> extend_set h A ⊆ extend_set h B"
by (unfold extend_set_def, blast)
```

context *Extend*
begin

lemma *mem_extend_set_iff [iff]: "z ∈ extend_set h A = (f z ∈ A)"*
apply *(unfold extend_set_def)*
apply *(force intro: h_f_g_eq [symmetric])*
done

lemma *extend_set_strict_mono [iff]:*
"(extend_set h A ⊆ extend_set h B) = (A ⊆ B)"
by *(unfold extend_set_def, force)*

lemma *(***in** *-) extend_set_empty [simp]: "extend_set h {} = {}"*
by *(unfold extend_set_def, auto)*

lemma *extend_set_eq_Collect: "extend_set h {s. P s} = {s. P(f s)}"*
by *auto*

lemma *extend_set_sing: "extend_set h {x} = {s. f s = x}"*
by *auto*

lemma *extend_set_inverse [simp]: "project_set h (extend_set h C) = C"*
by *(unfold extend_set_def, auto)*

lemma *extend_set_project_set: "C ⊆ extend_set h (project_set h C)"*
apply *(unfold extend_set_def)*
apply *(auto simp add: split_extended_all, blast)*
done

lemma *inj_extend_set: "inj (extend_set h)"*
apply *(rule inj_on_inverseI)*
apply *(rule extend_set_inverse)*
done

lemma *extend_set_UNIV_eq [simp]: "extend_set h UNIV = UNIV"*
apply *(unfold extend_set_def)*
apply *(auto simp add: split_extended_all)*
done

10.4 *project_set*: basic properties

lemma *project_set_eq: "project_set h C = f ‘ C"*
by *(auto intro: f_h_eq [symmetric] simp add: split_extended_all)*

lemma *project_set_I: "!!z. z ∈ C ==> f z ∈ project_set h C"*
by *(auto simp add: split_extended_all)*

10.5 More laws

lemma *project_set_extend_set_Int: "project_set h ((extend_set h A) ∩ B) =*
A ∩ (project_set h B)"
by *auto*

lemma *project_set_extend_set_Un: "project_set h ((extend_set h A) ∪ B) = A ∪ (project_set h B)"*
by *auto*

lemma (**in** *-*) *project_set_Int_subset:*
"project_set h (A ∩ B) ⊆ (project_set h A) ∩ (project_set h B)"
by *auto*

lemma *extend_set_Un_distrib: "extend_set h (A ∪ B) = extend_set h A ∪ extend_set h B"*
by *auto*

lemma *extend_set_Int_distrib: "extend_set h (A ∩ B) = extend_set h A ∩ extend_set h B"*
by *auto*

lemma *extend_set_INT_distrib: "extend_set h (⋂(B ‘ A)) = (⋂x ∈ A. extend_set h (B x))"*
by *auto*

lemma *extend_set_Diff_distrib: "extend_set h (A - B) = extend_set h A - extend_set h B"*
by *auto*

lemma *extend_set_Union: "extend_set h (⋃A) = (⋃X ∈ A. extend_set h X)"*
by *blast*

lemma *extend_set_subset_Compl_eq: "(extend_set h A ⊆ - extend_set h B) = (A ⊆ - B)"*
by *(auto simp: extend_set_def)*

10.6 *extend_act*

lemma *mem_extend_act_iff [iff]: "((h(s,y), h(s’,y)) ∈ extend_act h act) = ((s, s’) ∈ act)"*
by *(auto simp: extend_act_def)*

lemma *extend_act_D: "(z, z’) ∈ extend_act h act ==> (f z, f z’) ∈ act"*
by *(auto simp: extend_act_def)*

lemma *extend_act_inverse [simp]: "project_act h (extend_act h act) = act"*
unfolding *extend_act_def project_act_def* **by** *blast*

lemma *project_act_extend_act_restrict [simp]:*
"project_act h (Restrict C (extend_act h act)) =
Restrict (project_set h C) act"
unfolding *extend_act_def project_act_def* **by** *blast*

lemma *subset_extend_act_D: "act’ ⊆ extend_act h act ==> project_act h act’ ⊆ act"*
unfolding *extend_act_def project_act_def* **by** *force*

```
lemma inj_extend_act: "inj (extend_act h)"
apply (rule inj_on_inverseI)
apply (rule extend_act_inverse)
done

lemma extend_act_Image [simp]:
     "extend_act h act `` (extend_set h A) = extend_set h (act `` A)"
  unfolding extend_set_def extend_act_def by force

lemma extend_act_strict_mono [iff]:
     "(extend_act h act' ⊆ extend_act h act) = (act'<=act)"
  by (auto simp: extend_act_def)

lemma [iff]: "(extend_act h act = extend_act h act') = (act = act')"
  by (rule inj_extend_act [THEN inj_eq])

lemma (in -) Domain_extend_act:
    "Domain (extend_act h act) = extend_set h (Domain act)"
  unfolding extend_set_def extend_act_def by force

lemma extend_act_Id [simp]: "extend_act h Id = Id"
  unfolding extend_act_def by (force intro: h_f_g_eq [symmetric])

lemma project_act_I:  "!!z z'. (z, z') ∈ act ==> (f z, f z') ∈ project_act
h act"
  unfolding project_act_def by (force simp add: split_extended_all)

lemma project_act_Id [simp]: "project_act h Id = Id"
  unfolding project_act_def by force

lemma Domain_project_act: "Domain (project_act h act) = project_set h (Domain
act)"
  unfolding project_act_def by (force simp add: split_extended_all)
```

10.7 extend

Basic properties

```
lemma (in -) Init_extend [simp]:
     "Init (extend h F) = extend_set h (Init F)"
  by (auto simp: extend_def)

lemma (in -) Init_project [simp]:
     "Init (project h C F) = project_set h (Init F)"
  by (auto simp: project_def)

lemma Acts_extend [simp]: "Acts (extend h F) = (extend_act h ` Acts F)"
  by (simp add: extend_def insert_Id_image_Acts)

lemma AllowedActs_extend [simp]:
     "AllowedActs (extend h F) = project_act h -` AllowedActs F"
  by (simp add: extend_def insert_absorb)
```

```
lemma (in -) Acts_project [simp]:
     "Acts(project h C F) = insert Id (project_act h ‘ Restrict C ‘ Acts F)"
  by (auto simp add: project_def image_iff)

lemma AllowedActs_project [simp]:
     "AllowedActs(project h C F) =
        {act. Restrict (project_set h C) act
               ∈ project_act h ‘ Restrict C ‘ AllowedActs F}"
apply (simp (no_asm) add: project_def image_iff)
apply (subst insert_absorb)
apply (auto intro!: bexI [of _ Id] simp add: project_act_def)
done

lemma Allowed_extend: "Allowed (extend h F) = project h UNIV -‘ Allowed F"
  by (auto simp add: Allowed_def)

lemma extend_SKIP [simp]: "extend h SKIP = SKIP"
apply (unfold SKIP_def)
apply (rule program_equalityI, auto)
done

lemma (in -) project_set_UNIV [simp]: "project_set h UNIV = UNIV"
  by auto

lemma (in -) project_set_Union: "project_set h (⋃A) = (⋃X ∈ A. project_set
h X)"
  by blast



lemma (in -) project_act_Restrict_subset:
     "project_act h (Restrict C act) ⊆ Restrict (project_set h C) (project_act
h act)"
  by (auto simp add: project_act_def)

lemma project_act_Restrict_Id_eq: "project_act h (Restrict C Id) = Restrict
(project_set h C) Id"
  by (auto simp add: project_act_def)

lemma project_extend_eq:
     "project h C (extend h F) =
      mk_program (Init F, Restrict (project_set h C) ‘ Acts F,
                  {act. Restrict (project_set h C) act
                          ∈ project_act h ‘ Restrict C ‘
                                  (project_act h -‘ AllowedActs F)})"
apply (rule program_equalityI)
  apply simp
 apply (simp add: image_image)
apply (simp add: project_def)
done

lemma extend_inverse [simp]:
     "project h UNIV (extend h F) = F"
apply (simp (no_asm_simp) add: project_extend_eq
```

```
          subset_UNIV [THEN subset_trans, THEN Restrict_triv])
apply (rule program_equalityI)
apply (simp_all (no_asm))
apply (subst insert_absorb)
apply (simp (no_asm) add: bexI [of _ Id])
apply auto
apply (simp add: image_def)
using project_act_Id apply blast
apply (simp add: image_def)
apply (rename_tac "act")
apply (rule_tac x = "extend_act h act" in exI)
apply simp
done

lemma inj_extend: "inj (extend h)"
apply (rule inj_on_inverseI)
apply (rule extend_inverse)
done

lemma extend_Join [simp]: "extend h (F⊔G) = extend h F⊔extend h G"
apply (rule program_equalityI)
apply (simp (no_asm) add: extend_set_Int_distrib)
apply (simp add: image_Un, auto)
done

lemma extend_JN [simp]: "extend h (JOIN I F) = (⨆i ∈ I. extend h (F i))"
apply (rule program_equalityI)
  apply (simp (no_asm) add: extend_set_INT_distrib)
 apply (simp add: image_UN, auto)
done



lemma extend_mono: "F ≤ G ==> extend h F ≤ extend h G"
  by (force simp add: component_eq_subset)

lemma project_mono: "F ≤ G ==> project h C F ≤ project h C G"
  by (simp add: component_eq_subset, blast)

lemma all_total_extend: "all_total F ==> all_total (extend h F)"
  by (simp add: all_total_def Domain_extend_act)
```

10.8 Safety: co, stable

```
lemma extend_constrains:
     "(extend h F ∈ (extend_set h A) co (extend_set h B)) =
      (F ∈ A co B)"
  by (simp add: constrains_def)

lemma extend_stable:
     "(extend h F ∈ stable (extend_set h A)) = (F ∈ stable A)"
  by (simp add: stable_def extend_constrains)

lemma extend_invariant:
```

```
    "(extend h F ∈ invariant (extend_set h A)) = (F ∈ invariant A)"
  by (simp add: invariant_def extend_stable)


lemma extend_constrains_project_set:
    "extend h F ∈ A co B ==> F ∈ (project_set h A) co (project_set h B)"
  by (auto simp add: constrains_def, force)

lemma extend_stable_project_set:
    "extend h F ∈ stable A ==> F ∈ stable (project_set h A)"
  by (simp add: stable_def extend_constrains_project_set)
```

10.9 Weak safety primitives: Co, Stable

```
lemma reachable_extend_f: "p ∈ reachable (extend h F) ==> f p ∈ reachable
F"
  by (induct set: reachable) (auto intro: reachable.intros simp add: extend_act_def
image_iff)

lemma h_reachable_extend: "h(s,y) ∈ reachable (extend h F) ==> s ∈ reachable
F"
  by (force dest!: reachable_extend_f)

lemma reachable_extend_eq: "reachable (extend h F) = extend_set h (reachable
F)"
apply (unfold extend_set_def)
apply (rule equalityI)
apply (force intro: h_f_g_eq [symmetric] dest!: reachable_extend_f, clarify)
apply (erule reachable.induct)
apply (force intro: reachable.intros)+
done

lemma extend_Constrains:
    "(extend h F ∈ (extend_set h A) Co (extend_set h B)) =
     (F ∈ A Co B)"
  by (simp add: Constrains_def reachable_extend_eq extend_constrains
            extend_set_Int_distrib [symmetric])

lemma extend_Stable: "(extend h F ∈ Stable (extend_set h A)) = (F ∈ Stable
A)"
  by (simp add: Stable_def extend_Constrains)

lemma extend_Always: "(extend h F ∈ Always (extend_set h A)) = (F ∈ Always
A)"
  by (simp add: Always_def extend_Stable)




lemma (in -) project_act_mono:
    "D ⊆ C ==>
     project_act h (Restrict D act) ⊆ project_act h (Restrict C act)"
```

```
  by (auto simp add: project_act_def)

lemma project_constrains_mono:
     "[| D ⊆ C; project h C F ∈ A co B |] ==> project h D F ∈ A co B"
apply (auto simp add: constrains_def)
apply (drule project_act_mono, blast)
done

lemma project_stable_mono:
     "[| D ⊆ C;  project h C F ∈ stable A |] ==> project h D F ∈ stable A"
  by (simp add: stable_def project_constrains_mono)


lemma project_constrains:
     "(project h C F ∈ A co B)  =
      (F ∈ (C ∩ extend_set h A) co (extend_set h B) & A ⊆ B)"
apply (unfold constrains_def)
apply (auto intro!: project_act_I simp add: ball_Un)
apply (force intro!: project_act_I dest!: subsetD)

apply (unfold project_act_def)
apply (force dest!: subsetD)
done

lemma project_stable: "(project h UNIV F ∈ stable A) = (F ∈ stable (extend_set
h A))"
  by (simp add: stable_def project_constrains)

lemma project_stable_I: "F ∈ stable (extend_set h A) ==> project h C F ∈
stable A"
apply (drule project_stable [THEN iffD2])
apply (blast intro: project_stable_mono)
done

lemma Int_extend_set_lemma:
     "A ∩ extend_set h ((project_set h A) ∩ B) = A ∩ extend_set h B"
  by (auto simp add: split_extended_all)


lemma project_constrains_project_set:
     "G ∈ C co B ==> project h C G ∈ project_set h C co project_set h B"
  by (simp add: constrains_def project_def project_act_def, blast)

lemma project_stable_project_set:
     "G ∈ stable C ==> project h C G ∈ stable (project_set h C)"
  by (simp add: stable_def project_constrains_project_set)
```

10.10 Progress: transient, ensures

```
lemma extend_transient:
     "(extend h F ∈ transient (extend_set h A)) = (F ∈ transient A)"
  by (auto simp add: transient_def extend_set_subset_Compl_eq Domain_extend_act)

lemma extend_ensures:
```

```
     "(extend h F ∈ (extend_set h A) ensures (extend_set h B)) =
      (F ∈ A ensures B)"
  by (simp add: ensures_def extend_constrains extend_transient
        extend_set_Un_distrib [symmetric] extend_set_Diff_distrib [symmetric])

lemma leadsTo_imp_extend_leadsTo:
     "F ∈ A leadsTo B
      ==> extend h F ∈ (extend_set h A) leadsTo (extend_set h B)"
apply (erule leadsTo_induct)
  apply (simp add: leadsTo_Basis extend_ensures)
 apply (blast intro: leadsTo_Trans)
apply (simp add: leadsTo_UN extend_set_Union)
done
```

10.11 Proving the converse takes some doing!

```
lemma slice_iff [iff]: "(x ∈ slice C y) = (h(x,y) ∈ C)"
  by (simp add: slice_def)

lemma slice_Union: "slice (⋃S) y = (⋃x ∈ S. slice x y)"
  by auto

lemma slice_extend_set: "slice (extend_set h A) y = A"
  by auto

lemma project_set_is_UN_slice: "project_set h A = (⋃y. slice A y)"
  by auto

lemma extend_transient_slice:
     "extend h F ∈ transient A ==> F ∈ transient (slice A y)"
  by (auto simp: transient_def)


lemma extend_constrains_slice:
     "extend h F ∈ A co B ==> F ∈ (slice A y) co (slice B y)"
  by (auto simp add: constrains_def)

lemma extend_ensures_slice:
     "extend h F ∈ A ensures B ==> F ∈ (slice A y) ensures (project_set h
B)"
apply (auto simp add: ensures_def extend_constrains extend_transient)
apply (erule_tac [2] extend_transient_slice [THEN transient_strengthen])
apply (erule extend_constrains_slice [THEN constrains_weaken], auto)
done

lemma leadsTo_slice_project_set:
     "∀y. F ∈ (slice B y) leadsTo CU ==> F ∈ (project_set h B) leadsTo CU"
apply (simp add: project_set_is_UN_slice)
apply (blast intro: leadsTo_UN)
done

lemma extend_leadsTo_slice [rule_format]:
     "extend h F ∈ AU leadsTo BU
      ==> ∀y. F ∈ (slice AU y) leadsTo (project_set h BU)"
```

```
apply (erule leadsTo_induct)
  apply (blast intro: extend_ensures_slice)
 apply (blast intro: leadsTo_slice_project_set leadsTo_Trans)
apply (simp add: leadsTo_UN slice_Union)
done

lemma extend_leadsTo:
     "(extend h F ∈ (extend_set h A) leadsTo (extend_set h B)) =
      (F ∈ A leadsTo B)"
apply safe
apply (erule_tac [2] leadsTo_imp_extend_leadsTo)
apply (drule extend_leadsTo_slice)
apply (simp add: slice_extend_set)
done

lemma extend_LeadsTo:
     "(extend h F ∈ (extend_set h A) LeadsTo (extend_set h B)) =
      (F ∈ A LeadsTo B)"
  by (simp add: LeadsTo_def reachable_extend_eq extend_leadsTo
              extend_set_Int_distrib [symmetric])
```

10.12 preserves

```
lemma project_preserves_I:
     "G ∈ preserves (v o f) ==> project h C G ∈ preserves v"
  by (auto simp add: preserves_def project_stable_I extend_set_eq_Collect)


lemma project_preserves_id_I:
     "G ∈ preserves f ==> project h C G ∈ preserves id"
  by (simp add: project_preserves_I)

lemma extend_preserves:
     "(extend h G ∈ preserves (v o f)) = (G ∈ preserves v)"
  by (auto simp add: preserves_def extend_stable [symmetric]
                  extend_set_eq_Collect)

lemma inj_extend_preserves: "inj h ==> (extend h G ∈ preserves g)"
  by (auto simp add: preserves_def extend_def extend_act_def stable_def
                  constrains_def g_def)
```

10.13 Guarantees

```
lemma project_extend_Join: "project h UNIV ((extend h F)⊔G) = F⊔(project
h UNIV G)"
  apply (rule program_equalityI)
  apply (auto simp add: project_set_extend_set_Int image_iff)
  apply (metis Un_iff extend_act_inverse image_iff)
  apply (metis Un_iff extend_act_inverse image_iff)
  done

lemma extend_Join_eq_extend_D:
     "(extend h F)⊔G = extend h H ==> H = F⊔(project h UNIV G)"
apply (drule_tac f = "project h UNIV" in arg_cong)
```

```
apply (simp add: project_extend_Join)
done



lemma ok_extend_imp_ok_project: "extend h F ok G ==> F ok project h UNIV
G"
apply (auto simp add: ok_def)
apply (drule subsetD)
apply (auto intro!: rev_image_eqI)
done

lemma ok_extend_iff: "(extend h F ok extend h G) = (F ok G)"
apply (simp add: ok_def, safe)
apply force+
done

lemma OK_extend_iff: "OK I (%i. extend h (F i)) = (OK I F)"
apply (unfold OK_def, safe)
apply (drule_tac x = i in bspec)
apply (drule_tac [2] x = j in bspec)
apply force+
done

lemma guarantees_imp_extend_guarantees:
     "F ∈ X guarantees Y ==>
      extend h F ∈ (extend h ` X) guarantees (extend h ` Y)"
apply (rule guaranteesI, clarify)
apply (blast dest: ok_extend_imp_ok_project extend_Join_eq_extend_D
                   guaranteesD)
done

lemma extend_guarantees_imp_guarantees:
     "extend h F ∈ (extend h ` X) guarantees (extend h ` Y)
      ==> F ∈ X guarantees Y"
apply (auto simp add: guar_def)
apply (drule_tac x = "extend h G" in spec)
apply (simp del: extend_Join
            add: extend_Join [symmetric] ok_extend_iff
                 inj_extend [THEN inj_image_mem_iff])
done

lemma extend_guarantees_eq:
     "(extend h F ∈ (extend h ` X) guarantees (extend h ` Y)) =
      (F ∈ X guarantees Y)"
  by (blast intro: guarantees_imp_extend_guarantees
                   extend_guarantees_imp_guarantees)

end

end
```

11 Renaming of State Sets

theory *Rename* **imports** *Extend* **begin**

definition *rename :: "['a => 'b, 'a program] => 'b program"* **where**
    "rename h == extend (%(x,u::unit). h x)"

declare *image_inv_f_f [simp] image_f_inv_f [simp]*

declare *Extend.intro [simp,intro]*

lemma *good_map_bij [simp,intro]: "bij h ==> good_map (%(x,u). h x)"*
apply *(rule good_mapI)*
apply *(unfold bij_def inj_on_def surj_def, auto)*
done

lemma *fst_o_inv_eq_inv: "bij h ==> fst (inv (%(x,u). h x) s) = inv h s"*
apply *(unfold bij_def split_def, clarify)*
apply *(subgoal_tac "surj (%p. h (fst p))")*
 prefer *2* **apply** *(simp add: surj_def)*
apply *(erule injD)*
apply *(simp (no_asm_simp) add: surj_f_inv_f)*
apply *(erule surj_f_inv_f)*
done

lemma *mem_rename_set_iff: "bij h ==> z ∈ h`A = (inv h z ∈ A)"*
by *(force simp add: bij_is_inj bij_is_surj [THEN surj_f_inv_f])*

lemma *extend_set_eq_image [simp]: "extend_set (%(x,u). h x) A = h`A"*
by *(force simp add: extend_set_def)*

lemma *Init_rename [simp]: "Init (rename h F) = h`(Init F)"*
by *(simp add: rename_def)*

11.1 inverse properties

lemma *extend_set_inv:*
     "bij h
      ==> extend_set (%(x,u::'c). inv h x) = project_set (%(x,u::'c). h x)"
apply *(unfold bij_def)*
apply *(rule ext)*
apply *(force simp add: extend_set_def project_set_def surj_f_inv_f)*
done

lemma *bij_extend_act_eq_project_act: "bij h*
      ==> extend_act (%(x,u::'c). h x) = project_act (%(x,u::'c). inv h x)"
apply *(rule ext)*
apply *(force simp add: extend_act_def project_act_def bij_def surj_f_inv_f)*
done

lemma *bij_extend_act: "bij h ==> bij (extend_act (%(x,u::'c). h x))"*

```
apply (rule bijI)
apply (rule Extend.inj_extend_act)
apply simp
apply (simp add: bij_extend_act_eq_project_act)
apply (rule surjI)
apply (rule Extend.extend_act_inverse)
apply (blast intro: bij_imp_bij_inv)
done

lemma bij_project_act: "bij h ==> bij (project_act (%(x,u::'c). h x))"
apply (frule bij_imp_bij_inv [THEN bij_extend_act])
apply (simp add: bij_extend_act_eq_project_act bij_imp_bij_inv inv_inv_eq)
done

lemma bij_inv_project_act_eq: "bij h ==> inv (project_act (%(x,u::'c). inv
h x)) =
                project_act (%(x,u::'c). h x)"
apply (simp (no_asm_simp) add: bij_extend_act_eq_project_act [symmetric])
apply (rule surj_imp_inv_eq)
apply (blast intro!: bij_extend_act bij_is_surj)
apply (simp (no_asm_simp) add: Extend.extend_act_inverse)
done

lemma extend_inv: "bij h
      ==> extend (%(x,u::'c). inv h x) = project (%(x,u::'c). h x) UNIV"
apply (frule bij_imp_bij_inv)
apply (rule ext)
apply (rule program_equalityI)
  apply (simp (no_asm_simp) add: extend_set_inv)
 apply (simp add: Extend.project_act_Id Extend.Acts_extend
          insert_Id_image_Acts bij_extend_act_eq_project_act inv_inv_eq)
apply (simp add: Extend.AllowedActs_extend Extend.AllowedActs_project
            bij_project_act bij_vimage_eq_inv_image bij_inv_project_act_eq)
done

lemma rename_inv_rename [simp]: "bij h ==> rename (inv h) (rename h F) =
F"
by (simp add: rename_def extend_inv Extend.extend_inverse)

lemma rename_rename_inv [simp]: "bij h ==> rename h (rename (inv h) F) =
F"
apply (frule bij_imp_bij_inv)
apply (erule inv_inv_eq [THEN subst], erule rename_inv_rename)
done

lemma rename_inv_eq: "bij h ==> rename (inv h) = inv (rename h)"
by (rule inv_equality [symmetric], auto)



lemma bij_extend: "bij h ==> bij (extend (%(x,u::'c). h x))"
apply (rule bijI)
apply (blast intro: Extend.inj_extend)
apply (rule_tac f = "extend (% (x,u) . inv h x)" in surjI)
```

```
apply (subst (1 2) inv_inv_eq [of h, symmetric], assumption+)
apply (simp add: bij_imp_bij_inv extend_inv [of "inv h"])
apply (simp add: inv_inv_eq)
apply (rule Extend.extend_inverse)
apply (simp add: bij_imp_bij_inv)
done

lemma bij_project: "bij h ==> bij (project (%(x,u::'c). h x) UNIV)"
apply (subst extend_inv [symmetric])
apply (auto simp add: bij_imp_bij_inv bij_extend)
done

lemma inv_project_eq:
     "bij h
      ==> inv (project (%(x,u::'c). h x) UNIV) = extend (%(x,u::'c). h x)"
apply (rule inj_imp_inv_eq)
apply (erule bij_project [THEN bij_is_inj])
apply (simp (no_asm_simp) add: Extend.extend_inverse)
done

lemma Allowed_rename [simp]:
     "bij h ==> Allowed (rename h F) = rename h ` Allowed F"
apply (simp (no_asm_simp) add: rename_def Extend.Allowed_extend)
apply (subst bij_vimage_eq_inv_image)
apply (rule bij_project, blast)
apply (simp (no_asm_simp) add: inv_project_eq)
done

lemma bij_rename: "bij h ==> bij (rename h)"
apply (simp (no_asm_simp) add: rename_def bij_extend)
done
lemmas surj_rename = bij_rename [THEN bij_is_surj]

lemma inj_rename_imp_inj: "inj (rename h) ==> inj h"
apply (unfold inj_on_def, auto)
apply (drule_tac x = "mk_program ({x}, {}, {})" in spec)
apply (drule_tac x = "mk_program ({y}, {}, {})" in spec)
apply (auto simp add: program_equality_iff rename_def extend_def)
done

lemma surj_rename_imp_surj: "surj (rename h) ==> surj h"
apply (unfold surj_def, auto)
apply (drule_tac x = "mk_program ({y}, {}, {})" in spec)
apply (auto simp add: program_equality_iff rename_def extend_def)
done

lemma bij_rename_imp_bij: "bij (rename h) ==> bij h"
apply (unfold bij_def)
apply (simp (no_asm_simp) add: inj_rename_imp_inj surj_rename_imp_surj)
done

lemma bij_rename_iff [simp]: "bij (rename h) = bij h"
by (blast intro: bij_rename bij_rename_imp_bij)
```

11.2 the lattice operations

lemma *rename_SKIP [simp]: "bij h ==> rename h SKIP = SKIP"*
by *(simp add: rename_def Extend.extend_SKIP)*

lemma *rename_Join [simp]:*
"bij h ==> rename h (F ⊔ G) = rename h F ⊔ rename h G"
by *(simp add: rename_def Extend.extend_Join)*

lemma *rename_JN [simp]:*
"bij h ==> rename h (JOIN I F) = (⨆i ∈ I. rename h (F i))"
by *(simp add: rename_def Extend.extend_JN)*

11.3 Strong Safety: co, stable

lemma *rename_constrains:*
"bij h ==> (rename h F ∈ (h‘A) co (h‘B)) = (F ∈ A co B)"
apply *(unfold rename_def)*
apply *(subst extend_set_eq_image [symmetric])+*
apply *(erule good_map_bij [THEN Extend.intro, THEN Extend.extend_constrains])*
done

lemma *rename_stable:*
"bij h ==> (rename h F ∈ stable (h‘A)) = (F ∈ stable A)"
apply *(simp add: stable_def rename_constrains)*
done

lemma *rename_invariant:*
"bij h ==> (rename h F ∈ invariant (h‘A)) = (F ∈ invariant A)"
apply *(simp add: invariant_def rename_stable bij_is_inj [THEN inj_image_subset_iff])*
done

lemma *rename_increasing:*
"bij h ==> (rename h F ∈ increasing func) = (F ∈ increasing (func o h))"
apply *(simp add: increasing_def rename_stable [symmetric] bij_image_Collect_eq bij_is_surj [THEN surj_f_inv_f])*
done

11.4 Weak Safety: Co, Stable

lemma *reachable_rename_eq:*
"bij h ==> reachable (rename h F) = h ‘ (reachable F)"
apply *(simp add: rename_def Extend.reachable_extend_eq)*
done

lemma *rename_Constrains:*
"bij h ==> (rename h F ∈ (h‘A) Co (h‘B)) = (F ∈ A Co B)"
by *(simp add: Constrains_def reachable_rename_eq rename_constrains bij_is_inj image_Int [symmetric])*

lemma *rename_Stable:*
"bij h ==> (rename h F ∈ Stable (h‘A)) = (F ∈ Stable A)"
by *(simp add: Stable_def rename_Constrains)*

lemma *rename_Always: "bij h ==> (rename h F ∈ Always (h‘A)) = (F ∈ Always A)"*
by *(simp add: Always_def rename_Stable bij_is_inj [THEN inj_image_subset_iff])*

lemma *rename_Increasing:*
"bij h ==> (rename h F ∈ Increasing func) = (F ∈ Increasing (func o h))"
by *(simp add: Increasing_def rename_Stable [symmetric] bij_image_Collect_eq*

bij_is_surj [THEN surj_f_inv_f])

11.5 Progress: transient, ensures

lemma *rename_transient:*
"bij h ==> (rename h F ∈ transient (h‘A)) = (F ∈ transient A)"
apply *(unfold rename_def)*
apply *(subst extend_set_eq_image [symmetric])*
apply *(erule good_map_bij [THEN Extend.intro, THEN Extend.extend_transient])*
done

lemma *rename_ensures:*
"bij h ==> (rename h F ∈ (h‘A) ensures (h‘B)) = (F ∈ A ensures B)"
apply *(unfold rename_def)*
apply *(subst extend_set_eq_image [symmetric])+*
apply *(erule good_map_bij [THEN Extend.intro, THEN Extend.extend_ensures])*
done

lemma *rename_leadsTo:*
"bij h ==> (rename h F ∈ (h‘A) leadsTo (h‘B)) = (F ∈ A leadsTo B)"
apply *(unfold rename_def)*
apply *(subst extend_set_eq_image [symmetric])+*
apply *(erule good_map_bij [THEN Extend.intro, THEN Extend.extend_leadsTo])*
done

lemma *rename_LeadsTo:*
"bij h ==> (rename h F ∈ (h‘A) LeadsTo (h‘B)) = (F ∈ A LeadsTo B)"
apply *(unfold rename_def)*
apply *(subst extend_set_eq_image [symmetric])+*
apply *(erule good_map_bij [THEN Extend.intro, THEN Extend.extend_LeadsTo])*
done

lemma *rename_rename_guarantees_eq:*
"bij h ==> (rename h F ∈ (rename h ‘ X) guarantees
(rename h ‘ Y)) =
(F ∈ X guarantees Y)"
apply *(unfold rename_def)*
apply *(subst good_map_bij [THEN Extend.intro, THEN Extend.extend_guarantees_eq [symmetric]], assumption)*
apply *(simp (no_asm_simp) add: fst_o_inv_eq_inv o_def)*
done

lemma *rename_guarantees_eq_rename_inv:*
"bij h ==> (rename h F ∈ X guarantees Y) =
(F ∈ (rename (inv h) ‘ X) guarantees

```
                    (rename (inv h) ` Y))"
apply (subst rename_rename_guarantees_eq [symmetric], assumption)
apply (simp add: o_def bij_is_surj [THEN surj_f_inv_f] image_comp)
done

lemma rename_preserves:
     "bij h ==> (rename h G ∈ preserves v) = (G ∈ preserves (v o h))"
apply (subst good_map_bij [THEN Extend.intro, THEN Extend.extend_preserves
[symmetric]], assumption)
apply (simp add: o_def fst_o_inv_eq_inv rename_def bij_is_surj [THEN surj_f_inv_f])
done

lemma ok_rename_iff [simp]: "bij h ==> (rename h F ok rename h G) = (F ok
G)"
by (simp add: Extend.ok_extend_iff rename_def)

lemma OK_rename_iff [simp]: "bij h ==> OK I (%i. rename h (F i)) = (OK I
F)"
by (simp add: Extend.OK_extend_iff rename_def)
```

11.6 "image" versions of the rules, for lifting "guarantees" properties

```
lemmas bij_eq_rename = surj_rename [THEN surj_f_inv_f, symmetric]

lemma rename_image_constrains:
     "bij h ==> rename h ` (A co B) = (h ` A) co (h`B)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_constrains)
done

lemma rename_image_stable: "bij h ==> rename h ` stable A = stable (h ` A)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_stable)
done

lemma rename_image_increasing:
     "bij h ==> rename h ` increasing func = increasing (func o inv h)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_increasing o_def bij_is_inj)

done

lemma rename_image_invariant:
     "bij h ==> rename h ` invariant A = invariant (h ` A)"
```

```
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_invariant)
done

lemma rename_image_Constrains:
     "bij h ==> rename h ` (A Co B) = (h ` A) Co (h`B)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_Constrains)
done

lemma rename_image_preserves:
     "bij h ==> rename h ` preserves v = preserves (v o inv h)"
by (simp add: o_def rename_image_stable preserves_def bij_image_INT
              bij_image_Collect_eq)

lemma rename_image_Stable:
     "bij h ==> rename h ` Stable A = Stable (h ` A)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_Stable)
done

lemma rename_image_Increasing:
     "bij h ==> rename h ` Increasing func = Increasing (func o inv h)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_Increasing o_def bij_is_inj)
done

lemma rename_image_Always: "bij h ==> rename h ` Always A = Always (h ` A)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_Always)
done

lemma rename_image_leadsTo:
     "bij h ==> rename h ` (A leadsTo B) = (h ` A) leadsTo (h`B)"
apply auto
 defer 1
 apply (rename_tac F)
 apply (subgoal_tac "∃G. F = rename h G")
 apply (auto intro!: bij_eq_rename simp add: rename_leadsTo)
```

done

lemma *rename_image_LeadsTo:*
"bij h ==> rename h ‘ (A LeadsTo B) = (h ‘ A) LeadsTo (h‘B)"
apply *auto*
defer *1*
apply *(rename_tac F)*
apply *(subgoal_tac "∃G. F = rename h G")*
apply *(auto intro!: bij_eq_rename simp add: rename_LeadsTo)*
done

end

12 Replication of Components

theory *Lift_prog* **imports** *Rename* **begin**

definition *insert_map :: "[nat, 'b, nat=>'b] => (nat=>'b)"* **where**
"insert_map i z f k == if k<i then f k
else if k=i then z
else f(k - 1)"

definition *delete_map :: "[nat, nat=>'b] => (nat=>'b)"* **where**
"delete_map i g k == if k<i then g k else g (Suc k)"

definition *lift_map :: "[nat, 'b * ((nat=>'b) * 'c)] => (nat=>'b) * 'c"* **where**
"lift_map i == %(s,(f,uu)). (insert_map i s f, uu)"

definition *drop_map :: "[nat, (nat=>'b) * 'c] => 'b * ((nat=>'b) * 'c)"* **where**
"drop_map i == %(g, uu). (g i, (delete_map i g, uu))"

definition *lift_set :: "[nat, ('b * ((nat=>'b) * 'c)) set] => ((nat=>'b) * 'c) set"* **where**
"lift_set i A == lift_map i ‘ A"

definition *lift :: "[nat, ('b * ((nat=>'b) * 'c)) program] => ((nat=>'b) * 'c) program"* **where**
"lift i == rename (lift_map i)"

definition *sub :: "['a, 'a=>'b] => 'b"* **where**
"sub == %i f. f i"

declare *insert_map_def [simp] delete_map_def [simp]*

lemma *insert_map_inverse: "delete_map i (insert_map i x f) = f"*
by *(rule ext, simp)*

lemma *insert_map_delete_map_eq: "(insert_map i x (delete_map i g)) = g(i:=x)"*
apply *(rule ext)*
apply *(auto split: nat_diff_split)*
done

12.1 Injectiveness proof

lemma *insert_map_inject1: "(insert_map i x f) = (insert_map i y g) ==> x=y"*
by *(drule_tac x = i* **in** *fun_cong, simp)*

lemma *insert_map_inject2: "(insert_map i x f) = (insert_map i y g) ==> f=g"*
apply *(drule_tac f = "delete_map i"* **in** *arg_cong)*
apply *(simp add: insert_map_inverse)*
done

lemma *insert_map_inject':*
"(insert_map i x f) = (insert_map i y g) ==> x=y & f=g"
by *(blast dest: insert_map_inject1 insert_map_inject2)*

lemmas *insert_map_inject = insert_map_inject' [THEN conjE, elim!]*

lemma *lift_map_eq_iff [iff]:*
"(lift_map i (s,(f,uu)) = lift_map i' (s',(f',uu')))
= (uu = uu' & insert_map i s f = insert_map i' s' f')"
by *(unfold lift_map_def, auto)*

lemma *drop_map_lift_map_eq [simp]: "!!s. drop_map i (lift_map i s) = s"*
apply *(unfold lift_map_def drop_map_def)*
apply *(force intro: insert_map_inverse)*
done

lemma *inj_lift_map: "inj (lift_map i)"*
apply *(unfold lift_map_def)*
apply *(rule inj_onI, auto)*
done

12.2 Surjectiveness proof

lemma *lift_map_drop_map_eq [simp]: "!!s. lift_map i (drop_map i s) = s"*
apply *(unfold lift_map_def drop_map_def)*
apply *(force simp add: insert_map_delete_map_eq)*
done

lemma *drop_map_inject [dest!]: "(drop_map i s) = (drop_map i s') ==> s=s'"*
by *(drule_tac f = "lift_map i"* **in** *arg_cong, simp)*

lemma *surj_lift_map: "surj (lift_map i)"*
apply *(rule surjI)*
apply *(rule lift_map_drop_map_eq)*
done

lemma *bij_lift_map [iff]: "bij (lift_map i)"*
by *(simp add: bij_def inj_lift_map surj_lift_map)*

lemma *inv_lift_map_eq [simp]: "inv (lift_map i) = drop_map i"*
by *(rule inv_equality, auto)*

lemma *inv_drop_map_eq [simp]: "inv (drop_map i) = lift_map i"*

by *(rule inv_equality, auto)*

lemma *bij_drop_map [iff]: "bij (drop_map i)"*
by *(simp del: inv_lift_map_eq add: inv_lift_map_eq [symmetric] bij_imp_bij_inv)*

lemma *sub_apply [simp]: "sub i f = f i"*
by *(simp add: sub_def)*

lemma *all_total_lift: "all_total F ==> all_total (lift i F)"*
by *(simp add: lift_def rename_def Extend.all_total_extend)*

lemma *insert_map_upd_same: "(insert_map i t f)(i := s) = insert_map i s f"*
by *(rule ext, auto)*

lemma *insert_map_upd:*
"(insert_map j t f)(i := s) =
(if i=j then insert_map i s f
else if i<j then insert_map j t (f(i:=s))
else insert_map j t (f(i - Suc 0 := s)))"
apply *(rule ext)*
apply *(simp split: nat_diff_split)*

This simplification is VERY slow

done

lemma *insert_map_eq_diff:*
"[| insert_map i s f = insert_map j t g; i≠j |]
==> ∃g'. insert_map i s' f = insert_map j t g'"
apply *(subst insert_map_upd_same [symmetric])*
apply *(erule ssubst)*
apply *(simp only: insert_map_upd if_False split: if_split, blast)*
done

lemma *lift_map_eq_diff:*
"[| lift_map i (s,(f,uu)) = lift_map j (t,(g,vv)); i≠j |]
==> ∃g'. lift_map i (s',(f,uu)) = lift_map j (t,(g',vv))"
apply *(unfold lift_map_def, auto)*
apply *(blast dest: insert_map_eq_diff)*
done

12.3 The Operator *lift_set*

lemma *lift_set_empty [simp]: "lift_set i {} = {}"*
by *(unfold lift_set_def, auto)*

lemma *lift_set_iff: "(lift_map i x ∈ lift_set i A) = (x ∈ A)"*
apply *(unfold lift_set_def)*
apply *(rule inj_lift_map [THEN inj_image_mem_iff])*
done

lemma *lift_set_iff2 [iff]:*
"((f,uu) ∈ lift_set i A) = ((f i, (delete_map i f, uu)) ∈ A)"

by *(simp add: lift_set_def mem_rename_set_iff drop_map_def)*

lemma *lift_set_mono: "A ⊆ B ==> lift_set i A ⊆ lift_set i B"*
apply *(unfold lift_set_def)*
apply *(erule image_mono)*
done

lemma *lift_set_Un_distrib: "lift_set i (A ∪ B) = lift_set i A ∪ lift_set i B"*
by *(simp add: lift_set_def image_Un)*

lemma *lift_set_Diff_distrib: "lift_set i (A-B) = lift_set i A - lift_set i B"*
apply *(unfold lift_set_def)*
apply *(rule inj_lift_map [THEN image_set_diff])*
done

12.4 The Lattice Operations

lemma *bij_lift [iff]: "bij (lift i)"*
by *(simp add: lift_def)*

lemma *lift_SKIP [simp]: "lift i SKIP = SKIP"*
by *(simp add: lift_def)*

lemma *lift_Join [simp]: "lift i (F ⊔ G) = lift i F ⊔ lift i G"*
by *(simp add: lift_def)*

lemma *lift_JN [simp]: "lift j (JOIN I F) = (⨆i ∈ I. lift j (F i))"*
by *(simp add: lift_def)*

12.5 Safety: constrains, stable, invariant

lemma *lift_constrains:*
"(lift i F ∈ (lift_set i A) co (lift_set i B)) = (F ∈ A co B)"
by *(simp add: lift_def lift_set_def rename_constrains)*

lemma *lift_stable:*
"(lift i F ∈ stable (lift_set i A)) = (F ∈ stable A)"
by *(simp add: lift_def lift_set_def rename_stable)*

lemma *lift_invariant:*
"(lift i F ∈ invariant (lift_set i A)) = (F ∈ invariant A)"
by *(simp add: lift_def lift_set_def rename_invariant)*

lemma *lift_Constrains:*
"(lift i F ∈ (lift_set i A) Co (lift_set i B)) = (F ∈ A Co B)"
by *(simp add: lift_def lift_set_def rename_Constrains)*

lemma *lift_Stable:*
"(lift i F ∈ Stable (lift_set i A)) = (F ∈ Stable A)"
by *(simp add: lift_def lift_set_def rename_Stable)*

lemma *lift_Always:*
"(lift i F ∈ Always (lift_set i A)) = (F ∈ Always A)"
by (simp add: lift_def lift_set_def rename_Always)

12.6 Progress: transient, ensures

lemma *lift_transient:*
"(lift i F ∈ transient (lift_set i A)) = (F ∈ transient A)"
by (simp add: lift_def lift_set_def rename_transient)

lemma *lift_ensures:*
"(lift i F ∈ (lift_set i A) ensures (lift_set i B)) =
(F ∈ A ensures B)"
by (simp add: lift_def lift_set_def rename_ensures)

lemma *lift_leadsTo:*
"(lift i F ∈ (lift_set i A) leadsTo (lift_set i B)) =
(F ∈ A leadsTo B)"
by (simp add: lift_def lift_set_def rename_leadsTo)

lemma *lift_LeadsTo:*
"(lift i F ∈ (lift_set i A) LeadsTo (lift_set i B)) =
(F ∈ A LeadsTo B)"
by (simp add: lift_def lift_set_def rename_LeadsTo)

lemma *lift_lift_guarantees_eq:*
"(lift i F ∈ (lift i ‘ X) guarantees (lift i ‘ Y)) =
(F ∈ X guarantees Y)"
apply (unfold lift_def)
apply (subst bij_lift_map [THEN rename_rename_guarantees_eq, symmetric])
apply (simp add: o_def)
done

lemma *lift_guarantees_eq_lift_inv:*
"(lift i F ∈ X guarantees Y) =
(F ∈ (rename (drop_map i) ‘ X) guarantees (rename (drop_map i) ‘ Y))"
by (simp add: bij_lift_map [THEN rename_guarantees_eq_rename_inv] lift_def)

lemma *lift_preserves_snd_I: "F ∈ preserves snd ==> lift i F ∈ preserves snd"*
apply (drule_tac w1=snd **in** subset_preserves_o [THEN subsetD])
apply (simp add: lift_def rename_preserves)
apply (simp add: lift_map_def o_def split_def)
done

lemma *delete_map_eqE':*
"(delete_map i g) = (delete_map i g') ==> ∃x. g = g'(i:=x)"
apply (drule_tac f = "insert_map i (g i) " **in** arg_cong)
apply (simp add: insert_map_delete_map_eq)

```
apply (erule exI)
done

lemmas delete_map_eqE = delete_map_eqE' [THEN exE, elim!]

lemma delete_map_neq_apply:
     "[| delete_map j g = delete_map j g';  i≠j |] ==> g i = g' i"
by force



lemma vimage_o_fst_eq [simp]: "(f o fst) -‘ A = (f-‘A) × UNIV"
by auto

lemma vimage_sub_eq_lift_set [simp]:
     "(sub i -‘A) × UNIV = lift_set i (A × UNIV)"
by auto

lemma mem_lift_act_iff [iff]:
     "((s,s') ∈ extend_act (%(x,u::unit). lift_map i x) act) =
      ((drop_map i s, drop_map i s') ∈ act)"
apply (unfold extend_act_def, auto)
apply (rule bexI, auto)
done

lemma preserves_snd_lift_stable:
     "[| F ∈ preserves snd;  i≠j |]
      ==> lift j F ∈ stable (lift_set i (A × UNIV))"
apply (auto simp add: lift_def lift_set_def stable_def constrains_def
                      rename_def extend_def mem_rename_set_iff)
apply (auto dest!: preserves_imp_eq simp add: lift_map_def drop_map_def)
apply (drule_tac x = i in fun_cong, auto)
done


lemma constrains_imp_lift_constrains:
    "[| F i ∈ (A × UNIV) co (B × UNIV);
        F j ∈ preserves snd |]
     ==> lift j (F j) ∈ (lift_set i (A × UNIV)) co (lift_set i (B × UNIV))"
apply (cases "i=j")
apply (simp add: lift_def lift_set_def rename_constrains)
apply (erule preserves_snd_lift_stable[THEN stableD, THEN constrains_weaken_R],
       assumption)
apply (erule constrains_imp_subset [THEN lift_set_mono])
done


lemma lift_map_image_Times:
     "lift_map i ‘ (A × UNIV) =
      (⋃s ∈ A. ⋃f. {insert_map i s f}) × UNIV"
apply (auto intro!: bexI image_eqI simp add: lift_map_def)
apply (rule split_conv [symmetric])
done
```

```
lemma lift_preserves_eq:
     "(lift i F ∈ preserves v) = (F ∈ preserves (v o lift_map i))"
by (simp add: lift_def rename_preserves)


lemma lift_preserves_sub:
     "F ∈ preserves snd
      ==> lift i F ∈ preserves (v o sub j o fst) =
          (if i=j then F ∈ preserves (v o fst) else True)"
apply (drule subset_preserves_o [THEN subsetD])
apply (simp add: lift_preserves_eq o_def)
apply (auto cong del: if_weak_cong
       simp add: lift_map_def eq_commute split_def o_def)
done
```

12.7 Lemmas to Handle Function Composition (o) More Consistently

```
lemma o_equiv_assoc: "f o g = h ==> f' o f o g = f' o h"
by (simp add: fun_eq_iff o_def)

lemma o_equiv_apply: "f o g = h ==> ∀x. f(g x) = h x"
by (simp add: fun_eq_iff o_def)

lemma fst_o_lift_map: "sub i o fst o lift_map i = fst"
apply (rule ext)
apply (auto simp add: o_def lift_map_def sub_def)
done

lemma snd_o_lift_map: "snd o lift_map i = snd o snd"
apply (rule ext)
apply (auto simp add: o_def lift_map_def)
done
```

12.8 More lemmas about extend and project

They could be moved to theory Extend or Project

```
lemma extend_act_extend_act:
     "extend_act h' (extend_act h act) =
      extend_act (%(x,(y,y')). h'(h(x,y),y')) act"
apply (auto elim!: rev_bexI simp add: extend_act_def, blast)
done

lemma project_act_project_act:
     "project_act h (project_act h' act) =
      project_act (%(x,(y,y')). h'(h(x,y),y')) act"
by (auto elim!: rev_bexI simp add: project_act_def)

lemma project_act_extend_act:
     "project_act h (extend_act h' act) =
        {(x,x'). ∃s s' y y' z. (s,s') ∈ act &
                 h(x,y) = h'(s,z) & h(x',y') = h'(s',z)}"
by (simp add: extend_act_def project_act_def, blast)
```

12.9 OK and "lift"

```
lemma act_in_UNION_preserves_fst:
     "act ⊆ {(x,x'). fst x = fst x'} ==> act ∈ ⋃(Acts ` (preserves fst))"
apply (rule_tac a = "mk_program (UNIV,{act},UNIV) " in UN_I)
apply (auto simp add: preserves_def stable_def constrains_def)
done

lemma UNION_OK_lift_I:
     "[| ∀i ∈ I. F i ∈ preserves snd;
         ∀i ∈ I. ⋃(Acts ` (preserves fst)) ⊆ AllowedActs (F i) |]
      ==> OK I (%i. lift i (F i))"
apply (auto simp add: OK_def lift_def rename_def Extend.Acts_extend)
apply (simp add: Extend.AllowedActs_extend project_act_extend_act)
apply (rename_tac "act")
apply (subgoal_tac
       "{(x, x'). ∃s f u s' f' u'.
                    ((s, f, u), s', f', u') ∈ act &
                    lift_map j x = lift_map i (s, f, u) &
                    lift_map j x' = lift_map i (s', f', u') }
                ⊆ { (x,x') . fst x = fst x'}")
apply (blast intro: act_in_UNION_preserves_fst, clarify)
apply (drule_tac x = j in fun_cong)+
apply (drule_tac x = i in bspec, assumption)
apply (frule preserves_imp_eq, auto)
done

lemma OK_lift_I:
     "[| ∀i ∈ I. F i ∈ preserves snd;
         ∀i ∈ I. preserves fst ⊆ Allowed (F i) |]
      ==> OK I (%i. lift i (F i))"
by (simp add: safety_prop_AllowedActs_iff_Allowed UNION_OK_lift_I)

lemma Allowed_lift [simp]: "Allowed (lift i F) = lift i ` (Allowed F)"
by (simp add: lift_def)

lemma lift_image_preserves:
     "lift i ` preserves v = preserves (v o drop_map i)"
by (simp add: rename_image_preserves lift_def)

end


theory PPROD imports Lift_prog begin

definition PLam :: "[nat set, nat => ('b * ((nat=>'b) * 'c)) program]
            => ((nat=>'b) * 'c) program" where
    "PLam I F == ⨅i ∈ I. lift i (F i)"

syntax
  "_PLam" :: "[pttrn, nat set, 'b set] => (nat => 'b) set"  ("(3plam _:_./
_)" 10)
translations
  "plam x : A. B" == "CONST PLam A (%x. B)"
```

lemma *Init_PLam [simp]: "Init (PLam I F) = (⋂i ∈ I. lift_set i (Init (F i)))"*
by *(simp add: PLam_def lift_def lift_set_def)*

lemma *PLam_empty [simp]: "PLam {} F = SKIP"*
by *(simp add: PLam_def)*

lemma *PLam_SKIP [simp]: "(plam i : I. SKIP) = SKIP"*
by *(simp add: PLam_def JN_constant)*

lemma *PLam_insert: "PLam (insert i I) F = (lift i (F i)) ⊔ (PLam I F)"*
by *(unfold PLam_def, auto)*

lemma *PLam_component_iff: "((PLam I F) ≤ H) = (∀i ∈ I. lift i (F i) ≤ H)"*
by *(simp add: PLam_def JN_component_iff)*

lemma *component_PLam: "i ∈ I ==> lift i (F i) ≤ (PLam I F)"*
apply *(unfold PLam_def)*

apply *(fast intro: component_JN)*
done

lemma *PLam_constrains:*
"[| i ∈ I; ∀j. F j ∈ preserves snd |]
==> (PLam I F ∈ (lift_set i (A × UNIV)) co
(lift_set i (B × UNIV))) =
(F i ∈ (A × UNIV) co (B × UNIV))"
apply *(simp add: PLam_def JN_constrains)*
apply *(subst insert_Diff [symmetric], assumption)*
apply *(simp add: lift_constrains)*
apply *(blast intro: constrains_imp_lift_constrains)*
done

lemma *PLam_stable:*
"[| i ∈ I; ∀j. F j ∈ preserves snd |]
==> (PLam I F ∈ stable (lift_set i (A × UNIV))) =
(F i ∈ stable (A × UNIV))"
by *(simp add: stable_def PLam_constrains)*

lemma *PLam_transient:*
"i ∈ I ==>
PLam I F ∈ transient A = (∃i ∈ I. lift i (F i) ∈ transient A)"
by *(simp add: JN_transient PLam_def)*

This holds because the `F j` cannot change `lift_set i`

lemma *PLam_ensures:*
"[| i ∈ I; F i ∈ (A × UNIV) ensures (B × UNIV);

```
        ∀j. F j ∈ preserves snd |]
     ==> PLam I F ∈ lift_set i (A × UNIV) ensures lift_set i (B × UNIV)"
apply (simp add: ensures_def PLam_constrains PLam_transient
              lift_set_Un_distrib [symmetric] lift_set_Diff_distrib [symmetric]
              Times_Un_distrib1 [symmetric] Times_Diff_distrib1 [symmetric])
apply (rule rev_bexI, assumption)
apply (simp add: lift_transient)
done

lemma PLam_leadsTo_Basis:
     "[| i ∈ I;
         F i ∈ ((A × UNIV) - (B × UNIV)) co
               ((A × UNIV) ∪ (B × UNIV));
         F i ∈ transient ((A × UNIV) - (B × UNIV));
         ∀j. F j ∈ preserves snd |]
      ==> PLam I F ∈ lift_set i (A × UNIV) leadsTo lift_set i (B × UNIV)"
by (rule PLam_ensures [THEN leadsTo_Basis], rule_tac [2] ensuresI)




lemma invariant_imp_PLam_invariant:
     "[| F i ∈ invariant (A × UNIV);  i ∈ I;
         ∀j. F j ∈ preserves snd |]
      ==> PLam I F ∈ invariant (lift_set i (A × UNIV))"
by (auto simp add: PLam_stable invariant_def)


lemma PLam_preserves_fst [simp]:
     "∀j. F j ∈ preserves snd
      ==> (PLam I F ∈ preserves (v o sub j o fst)) =
          (if j ∈ I then F j ∈ preserves (v o fst) else True)"
by (simp add: PLam_def lift_preserves_sub)

lemma PLam_preserves_snd [simp,intro]:
     "∀j. F j ∈ preserves snd ==> PLam I F ∈ preserves snd"
by (simp add: PLam_def lift_preserves_snd_I)
```

This rule looks unsatisfactory because it refers to `lift`. One must use `lift_guarantees_eq_lift_inv` to rewrite the first subgoal and something like `lift_preserves_sub` to rewrite the third. However there's no obvious alternative for the third premise.

```
lemma guarantees_PLam_I:
    "[| lift i (F i) ∈ X guarantees Y;  i ∈ I;
        OK I (λi. lift i (F i)) |]
     ==> (PLam I F) ∈ X guarantees Y"
apply (unfold PLam_def)
apply (simp add: guarantees_JN_I)
done

lemma Allowed_PLam [simp]:
     "Allowed (PLam I F) = (⋂i ∈ I. lift i ` Allowed(F i))"
by (simp add: PLam_def)
```

```
lemma PLam_preserves [simp]:
     "(PLam I F) ∈ preserves v = (∀ i ∈ I. F i ∈ preserves (v o lift_map i))"
by (simp add: PLam_def lift_def rename_preserves)
```

```
end
```

13 The Prefix Ordering on Lists

```
theory ListOrder
imports Main
begin

inductive_set
  genPrefix :: "('a * 'a)set => ('a list * 'a list)set"
  for r :: "('a * 'a)set"
 where
   Nil:     "([],[]) ∈ genPrefix(r)"

 | prepend: "[| (xs,ys) ∈ genPrefix(r);  (x,y) ∈ r |] ==>
             (x#xs, y#ys) ∈ genPrefix(r)"

 | append:  "(xs,ys) ∈ genPrefix(r) ==> (xs, ys@zs) ∈ genPrefix(r)"

instantiation list :: (type) ord
begin

definition
  prefix_def:        "xs <= zs ⟷  (xs, zs) ∈ genPrefix Id"

definition
  strict_prefix_def: "xs < zs  ⟷  xs ≤ zs ∧ ¬ zs ≤ (xs :: 'a list)"

instance ..


end

definition Le :: "(nat*nat) set" where
    "Le == {(x,y). x <= y}"

definition  Ge :: "(nat*nat) set" where
    "Ge == {(x,y). y <= x}"

abbreviation
```

```
  pfixLe :: "[nat list, nat list] => bool"  (infixl "pfixLe" 50)  where
  "xs pfixLe ys == (xs,ys) ∈ genPrefix Le"

abbreviation
  pfixGe :: "[nat list, nat list] => bool"  (infixl "pfixGe" 50)  where
  "xs pfixGe ys == (xs,ys) ∈ genPrefix Ge"
```

13.1 preliminary lemmas

```
lemma Nil_genPrefix [iff]: "([], xs) ∈ genPrefix r"
by (cut_tac genPrefix.Nil [THEN genPrefix.append], auto)

lemma genPrefix_length_le: "(xs,ys) ∈ genPrefix r ⟹ length xs <= length
ys"
by (erule genPrefix.induct, auto)

lemma cdlemma:
     "[| (xs', ys') ∈ genPrefix r |]
      ==> (∀x xs. xs' = x#xs ⟶ (∃y ys. ys' = y#ys & (x,y) ∈ r & (xs, ys)
∈ genPrefix r))"
apply (erule genPrefix.induct, blast, blast)
apply (force intro: genPrefix.append)
done


lemma cons_genPrefixE [elim!]:
     "[| (x#xs, zs) ∈ genPrefix r;
         !!y ys. [| zs = y#ys;  (x,y) ∈ r;  (xs, ys) ∈ genPrefix r |] ==>
P
      |] ==> P"
by (drule cdlemma, simp, blast)

lemma Cons_genPrefix_Cons [iff]:
     "((x#xs,y#ys) ∈ genPrefix r) = ((x,y) ∈ r ∧ (xs,ys) ∈ genPrefix r)"
by (blast intro: genPrefix.prepend)
```

13.2 genPrefix is a partial order

```
lemma refl_genPrefix: "refl r ==> refl (genPrefix r)"
apply (unfold refl_on_def, auto)
apply (induct_tac "x")
prefer 2 apply (blast intro: genPrefix.prepend)
apply (blast intro: genPrefix.Nil)
done

lemma genPrefix_refl [simp]: "refl r ⟹ (l,l) ∈ genPrefix r"
by (erule refl_onD [OF refl_genPrefix UNIV_I])

lemma genPrefix_mono: "r<=s ==> genPrefix r <= genPrefix s"
apply clarify
apply (erule genPrefix.induct)
apply (auto intro: genPrefix.append)
done
```

```
lemma append_genPrefix:
     "(xs @ ys, zs) ∈ genPrefix r ⟹ (xs, zs) ∈ genPrefix r"
  by (induct xs arbitrary: zs) auto


lemma genPrefix_trans_O:
  assumes "(x, y) ∈ genPrefix r"
  shows "⋀z. (y, z) ∈ genPrefix s ⟹ (x, z) ∈ genPrefix (r O s)"
  apply (atomize (full))
  using assms
  apply induct
    apply blast
   apply (blast intro: genPrefix.prepend)
  apply (blast dest: append_genPrefix)
  done

lemma genPrefix_trans:
  "(x, y) ∈ genPrefix r ⟹ (y, z) ∈ genPrefix r ⟹ trans r
    ⟹ (x, z) ∈ genPrefix r"
  apply (rule trans_O_subset [THEN genPrefix_mono, THEN subsetD])
   apply assumption
  apply (blast intro: genPrefix_trans_O)
  done

lemma prefix_genPrefix_trans:
  "[| x<=y;  (y,z) ∈ genPrefix r |] ==> (x, z) ∈ genPrefix r"
apply (unfold prefix_def)
apply (drule genPrefix_trans_O, assumption)
apply simp
done

lemma genPrefix_prefix_trans:
  "[| (x,y) ∈ genPrefix r;  y<=z |] ==> (x,z) ∈ genPrefix r"
apply (unfold prefix_def)
apply (drule genPrefix_trans_O, assumption)
apply simp
done

lemma trans_genPrefix: "trans r ==> trans (genPrefix r)"
by (blast intro: transI genPrefix_trans)




lemma genPrefix_antisym:
  assumes 1: "(xs, ys) ∈ genPrefix r"
    and 2: "antisym r"
    and 3: "(ys, xs) ∈ genPrefix r"
  shows "xs = ys"
  using 1 3
```

```
proof induct
  case Nil
  then show ?case by blast
next
  case prepend
  then show ?case using 2 by (simp add: antisym_def)
next
  case (append xs ys zs)
  then show ?case
    apply -
    apply (subgoal_tac "length zs = 0", force)
    apply (drule genPrefix_length_le)+
    apply (simp del: length_0_conv)
    done
qed

lemma antisym_genPrefix: "antisym r ==> antisym (genPrefix r)"
  by (blast intro: antisymI genPrefix_antisym)
```

13.3 recursion equations

```
lemma genPrefix_Nil [simp]: "((xs, []) ∈ genPrefix r) = (xs = [])"
  by (induct xs) auto

lemma same_genPrefix_genPrefix [simp]:
    "refl r ⟹ ((xs@ys, xs@zs) ∈ genPrefix r) = ((ys,zs) ∈ genPrefix r)"
  by (induct xs) (simp_all add: refl_on_def)

lemma genPrefix_Cons:
     "((xs, y#ys) ∈ genPrefix r) =
      (xs=[] | (∃z zs. xs=z#zs & (z,y) ∈ r & (zs,ys) ∈ genPrefix r))"
  by (cases xs) auto

lemma genPrefix_take_append:
     "[| refl r;  (xs,ys) ∈ genPrefix r |]
      ==>  (xs@zs, take (length xs) ys @ zs) ∈ genPrefix r"
apply (erule genPrefix.induct)
apply (frule_tac [3] genPrefix_length_le)
apply (simp_all (no_asm_simp) add: diff_is_0_eq [THEN iffD2])
done

lemma genPrefix_append_both:
     "[| refl r;  (xs,ys) ∈ genPrefix r;  length xs = length ys |]
      ==>  (xs@zs, ys @ zs) ∈ genPrefix r"
apply (drule genPrefix_take_append, assumption)
apply simp
done



lemma append_cons_eq: "xs @ y # ys = (xs @ [y]) @ ys"
by auto

lemma aolemma:
```

```
     "[| (xs,ys) ∈ genPrefix r;  refl r |]
      ==> length xs < length ys ⟶ (xs @ [ys ! length xs], ys) ∈ genPrefix
r"
apply (erule genPrefix.induct)
  apply blast
 apply simp
```

Append case is hardest

```
apply simp
apply (frule genPrefix_length_le [THEN le_imp_less_or_eq])
apply (erule disjE)
apply (simp_all (no_asm_simp) add: neq_Nil_conv nth_append)
apply (blast intro: genPrefix.append, auto)
apply (subst append_cons_eq, fast intro: genPrefix_append_both genPrefix.append)
done

lemma append_one_genPrefix:
     "[| (xs,ys) ∈ genPrefix r;  length xs < length ys;  refl r |]
      ==> (xs @ [ys ! length xs], ys) ∈ genPrefix r"
by (blast intro: aolemma [THEN mp])




lemma genPrefix_imp_nth:
    "i < length xs ⟹ (xs, ys) ∈ genPrefix r ⟹ (xs ! i, ys ! i) ∈ r"
  apply (induct xs arbitrary: i ys)
   apply auto
  apply (case_tac i)
   apply auto
  done

lemma nth_imp_genPrefix:
  "length xs <= length ys ⟹
     (∀i. i < length xs ⟶ (xs ! i, ys ! i) ∈ r) ⟹
     (xs, ys) ∈ genPrefix r"
  apply (induct xs arbitrary: ys)
   apply (simp_all add: less_Suc_eq_0_disj all_conj_distrib)
  apply (case_tac ys)
   apply (force+)
  done

lemma genPrefix_iff_nth:
     "((xs,ys) ∈ genPrefix r) =
      (length xs <= length ys & (∀i. i < length xs ⟶ (xs!i, ys!i) ∈ r))"
apply (blast intro: genPrefix_length_le genPrefix_imp_nth nth_imp_genPrefix)
done
```

13.4 The type of lists is partially ordered

```
declare refl_Id [iff]
        antisym_Id [iff]
        trans_Id [iff]
```

```
lemma prefix_refl [iff]: "xs <= (xs::'a list)"
by (simp add: prefix_def)

lemma prefix_trans: "!!xs::'a list. [| xs <= ys; ys <= zs |] ==> xs <= zs"
apply (unfold prefix_def)
apply (blast intro: genPrefix_trans)
done

lemma prefix_antisym: "!!xs::'a list. [| xs <= ys; ys <= xs |] ==> xs = ys"
apply (unfold prefix_def)
apply (blast intro: genPrefix_antisym)
done

lemma prefix_less_le_not_le: "!!xs::'a list. (xs < zs) = (xs <= zs & ¬ zs
≤ xs)"
by (unfold strict_prefix_def, auto)

instance list :: (type) order
  by (intro_classes,
      (assumption | rule prefix_refl prefix_trans prefix_antisym
                    prefix_less_le_not_le)+)


lemma set_mono: "xs <= ys ==> set xs <= set ys"
apply (unfold prefix_def)
apply (erule genPrefix.induct, auto)
done




lemma Nil_prefix [iff]: "[] <= xs"
by (simp add: prefix_def)

lemma prefix_Nil [simp]: "(xs <= []) = (xs = [])"
by (simp add: prefix_def)

lemma Cons_prefix_Cons [simp]: "(x#xs <= y#ys) = (x=y & xs<=ys)"
by (simp add: prefix_def)

lemma same_prefix_prefix [simp]: "(xs@ys <= xs@zs) = (ys <= zs)"
by (simp add: prefix_def)

lemma append_prefix [iff]: "(xs@ys <= xs) = (ys <= [])"
by (insert same_prefix_prefix [of xs ys "[]"], simp)

lemma prefix_appendI [simp]: "xs <= ys ==> xs <= ys@zs"
apply (unfold prefix_def)
apply (erule genPrefix.append)
done

lemma prefix_Cons:
   "(xs <= y#ys) = (xs=[] | (∃zs. xs=y#zs ∧ zs <= ys))"
by (simp add: prefix_def genPrefix_Cons)
```

```
lemma append_one_prefix:
  "[| xs <= ys; length xs < length ys |] ==> xs @ [ys ! length xs] <= ys"
apply (unfold prefix_def)
apply (simp add: append_one_genPrefix)
done

lemma prefix_length_le: "xs <= ys ==> length xs <= length ys"
apply (unfold prefix_def)
apply (erule genPrefix_length_le)
done

lemma splemma: "xs<=ys ==> xs~=ys --> length xs < length ys"
apply (unfold prefix_def)
apply (erule genPrefix.induct, auto)
done

lemma strict_prefix_length_less: "xs < ys ==> length xs < length ys"
apply (unfold strict_prefix_def)
apply (blast intro: splemma [THEN mp])
done

lemma mono_length: "mono length"
by (blast intro: monoI prefix_length_le)


lemma prefix_iff: "(xs <= zs) = (∃ys. zs = xs@ys)"
apply (unfold prefix_def)
apply (auto simp add: genPrefix_iff_nth nth_append)
apply (rule_tac x = "drop (length xs) zs" in exI)
apply (rule nth_equalityI)
apply (simp_all (no_asm_simp) add: nth_append)
done

lemma prefix_snoc [simp]: "(xs <= ys@[y]) = (xs = ys@[y] | xs <= ys)"
apply (simp add: prefix_iff)
apply (rule iffI)
 apply (erule exE)
 apply (rename_tac "zs")
 apply (rule_tac xs = zs in rev_exhaust)
  apply simp
 apply clarify
 apply (simp del: append_assoc add: append_assoc [symmetric], force)
done

lemma prefix_append_iff:
     "(xs <= ys@zs) = (xs <= ys | (∃us. xs = ys@us & us <= zs))"
apply (rule_tac xs = zs in rev_induct)
 apply force
apply (simp del: append_assoc add: append_assoc [symmetric], force)
done


lemma common_prefix_linear:
```

fixes *xs ys zs :: "'a list"*
shows *"xs <= zs ⟹ ys <= zs ⟹ xs <= ys | ys <= xs"*
by *(induct zs rule: rev_induct) auto*

13.5 pfixLe, pfixGe: properties inherited from the translations

lemma *refl_Le [iff]: "refl Le"*
by *(unfold refl_on_def Le_def, auto)*

lemma *antisym_Le [iff]: "antisym Le"*
by *(unfold antisym_def Le_def, auto)*

lemma *trans_Le [iff]: "trans Le"*
by *(unfold trans_def Le_def, auto)*

lemma *pfixLe_refl [iff]: "x pfixLe x"*
by *simp*

lemma *pfixLe_trans: "[| x pfixLe y; y pfixLe z |] ==> x pfixLe z"*
by *(blast intro: genPrefix_trans)*

lemma *pfixLe_antisym: "[| x pfixLe y; y pfixLe x |] ==> x = y"*
by *(blast intro: genPrefix_antisym)*

lemma *prefix_imp_pfixLe: "xs<=ys ==> xs pfixLe ys"*
apply *(unfold prefix_def Le_def)*
apply *(blast intro: genPrefix_mono [THEN [2] rev_subsetD])*
done

lemma *refl_Ge [iff]: "refl Ge"*
by *(unfold refl_on_def Ge_def, auto)*

lemma *antisym_Ge [iff]: "antisym Ge"*
by *(unfold antisym_def Ge_def, auto)*

lemma *trans_Ge [iff]: "trans Ge"*
by *(unfold trans_def Ge_def, auto)*

lemma *pfixGe_refl [iff]: "x pfixGe x"*
by *simp*

lemma *pfixGe_trans: "[| x pfixGe y; y pfixGe z |] ==> x pfixGe z"*
by *(blast intro: genPrefix_trans)*

lemma *pfixGe_antisym: "[| x pfixGe y; y pfixGe x |] ==> x = y"*
by *(blast intro: genPrefix_antisym)*

lemma *prefix_imp_pfixGe: "xs<=ys ==> xs pfixGe ys"*
apply *(unfold prefix_def Ge_def)*
apply *(blast intro: genPrefix_mono [THEN [2] rev_subsetD])*
done

end

14 The Follows Relation of Charpentier and Sivilotte

```
theory Follows
imports SubstAx ListOrder "HOL-Library.Multiset"
begin

definition Follows :: "['a => 'b::{order}, 'a => 'b::{order}] => 'a program
set" (infixl "Fols" 65) where
   "f Fols g == Increasing g ∩ Increasing f Int
                Always {s. f s ≤ g s} Int
                (⋂k. {s. k ≤ g s} LeadsTo {s. k ≤ f s})"



lemma mono_Always_o:
     "mono h ==> Always {s. f s ≤ g s} ⊆ Always {s. h (f s) ≤ h (g s)}"
apply (simp add: Always_eq_includes_reachable)
apply (blast intro: monoD)
done

lemma mono_LeadsTo_o:
     "mono (h::'a::order => 'b::order)
      ==> (⋂j. {s. j ≤ g s} LeadsTo {s. j ≤ f s}) ⊆
          (⋂k. {s. k ≤ h (g s)} LeadsTo {s. k ≤ h (f s)})"
apply auto
apply (rule single_LeadsTo_I)
apply (drule_tac x = "g s" in spec)
apply (erule LeadsTo_weaken)
apply (blast intro: monoD order_trans)+
done

lemma Follows_constant [iff]: "F ∈ (%s. c) Fols (%s. c)"
by (simp add: Follows_def)

lemma mono_Follows_o:
  assumes "mono h"
  shows "f Fols g ⊆ (h o f) Fols (h o g)"
proof
  fix x
  assume "x ∈ f Fols g"
  with assms show "x ∈ (h ∘ f) Fols (h ∘ g)"
  by (auto simp add: Follows_def mono_Increasing_o [THEN [2] rev_subsetD]
    mono_Always_o [THEN [2] rev_subsetD]
    mono_LeadsTo_o [THEN [2] rev_subsetD, THEN INT_D])
qed

lemma mono_Follows_apply:
     "mono h ==> f Fols g ⊆ (%x. h (f x)) Fols (%x. h (g x))"
apply (drule mono_Follows_o)
apply (force simp add: o_def)
done

lemma Follows_trans:
     "[| F ∈ f Fols g;  F ∈ g Fols h |] ==> F ∈ f Fols h"
```

```
apply (simp add: Follows_def)
apply (simp add: Always_eq_includes_reachable)
apply (blast intro: order_trans LeadsTo_Trans)
done
```

14.1 Destruction rules

```
lemma Follows_Increasing1: "F ∈ f Fols g ==> F ∈ Increasing f"
by (simp add: Follows_def)

lemma Follows_Increasing2: "F ∈ f Fols g ==> F ∈ Increasing g"
by (simp add: Follows_def)

lemma Follows_Bounded: "F ∈ f Fols g ==> F ∈ Always {s. f s ≤ g s}"
by (simp add: Follows_def)

lemma Follows_LeadsTo:
     "F ∈ f Fols g ==> F ∈ {s. k ≤ g s} LeadsTo {s. k ≤ f s}"
by (simp add: Follows_def)

lemma Follows_LeadsTo_pfixLe:
     "F ∈ f Fols g ==> F ∈ {s. k pfixLe g s} LeadsTo {s. k pfixLe f s}"
apply (rule single_LeadsTo_I, clarify)
apply (drule_tac k="g s" in Follows_LeadsTo)
apply (erule LeadsTo_weaken)
 apply blast
apply (blast intro: pfixLe_trans prefix_imp_pfixLe)
done

lemma Follows_LeadsTo_pfixGe:
     "F ∈ f Fols g ==> F ∈ {s. k pfixGe g s} LeadsTo {s. k pfixGe f s}"
apply (rule single_LeadsTo_I, clarify)
apply (drule_tac k="g s" in Follows_LeadsTo)
apply (erule LeadsTo_weaken)
 apply blast
apply (blast intro: pfixGe_trans prefix_imp_pfixGe)
done


lemma Always_Follows1:
     "[| F ∈ Always {s. f s = f' s}; F ∈ f Fols g |] ==> F ∈ f' Fols g"

apply (simp add: Follows_def Increasing_def Stable_def, auto)
apply (erule_tac [3] Always_LeadsTo_weaken)
apply (erule_tac A = "{s. x ≤ f s}" and A' = "{s. x ≤ f s}"
       in Always_Constrains_weaken, auto)
apply (drule Always_Int_I, assumption)
apply (force intro: Always_weaken)
done

lemma Always_Follows2:
     "[| F ∈ Always {s. g s = g' s}; F ∈ f Fols g |] ==> F ∈ f Fols g'"
apply (simp add: Follows_def Increasing_def Stable_def, auto)
apply (erule_tac [3] Always_LeadsTo_weaken)
```

```
apply (erule_tac A = "{s. x ≤ g s}" and A' = "{s. x ≤ g s}"
       in Always_Constrains_weaken, auto)
apply (drule Always_Int_I, assumption)
apply (force intro: Always_weaken)
done
```

14.2 Union properties (with the subset ordering)

```
lemma increasing_Un:
    "[| F ∈ increasing f;  F ∈ increasing g |]
     ==> F ∈ increasing (%s. (f s) ∪ (g s))"
apply (simp add: increasing_def stable_def constrains_def, auto)
apply (drule_tac x = "f xb" in spec)
apply (drule_tac x = "g xb" in spec)
apply (blast dest!: bspec)
done

lemma Increasing_Un:
    "[| F ∈ Increasing f;  F ∈ Increasing g |]
     ==> F ∈ Increasing (%s. (f s) ∪ (g s))"
apply (auto simp add: Increasing_def Stable_def Constrains_def
                      stable_def constrains_def)
apply (drule_tac x = "f xb" in spec)
apply (drule_tac x = "g xb" in spec)
apply (blast dest!: bspec)
done


lemma Always_Un:
     "[| F ∈ Always {s. f' s ≤ f s}; F ∈ Always {s. g' s ≤ g s} |]
      ==> F ∈ Always {s. f' s ∪ g' s ≤ f s ∪ g s}"
by (simp add: Always_eq_includes_reachable, blast)


lemma Follows_Un_lemma:
     "[| F ∈ Increasing f; F ∈ Increasing g;
         F ∈ Increasing g'; F ∈ Always {s. f' s ≤ f s};
         ∀k. F ∈ {s. k ≤ f s} LeadsTo {s. k ≤ f' s} |]
      ==> F ∈ {s. k ≤ f s ∪ g s} LeadsTo {s. k ≤ f' s ∪ g s}"
apply (rule single_LeadsTo_I)
apply (drule_tac x = "f s" in IncreasingD)
apply (drule_tac x = "g s" in IncreasingD)
apply (rule LeadsTo_weaken)
apply (rule PSP_Stable)
apply (erule_tac x = "f s" in spec)
apply (erule Stable_Int, assumption, blast+)
done

lemma Follows_Un:
    "[| F ∈ f' Fols f;  F ∈ g' Fols g |]
     ==> F ∈ (%s. (f' s) ∪ (g' s)) Fols (%s. (f s) ∪ (g s))"
apply (simp add: Follows_def Increasing_Un Always_Un del: Un_subset_iff sup.bounded_iff,
auto)
apply (rule LeadsTo_Trans)
```

```
apply (blast intro: Follows_Un_lemma)

apply (blast intro: Follows_Un_lemma [THEN LeadsTo_weaken])
done
```

14.3 Multiset union properties (with the multiset ordering)

```
lemma increasing_union:
    "[| F ∈ increasing f;  F ∈ increasing g |]
     ==> F ∈ increasing (%s. (f s) + (g s :: ('a::order) multiset))"
apply (simp add: increasing_def stable_def constrains_def, auto)
apply (drule_tac x = "f xb" in spec)
apply (drule_tac x = "g xb" in spec)
apply (drule bspec, assumption)
apply (blast intro: add_mono order_trans)
done

lemma Increasing_union:
    "[| F ∈ Increasing f;  F ∈ Increasing g |]
     ==> F ∈ Increasing (%s. (f s) + (g s :: ('a::order) multiset))"
apply (auto simp add: Increasing_def Stable_def Constrains_def
                      stable_def constrains_def)
apply (drule_tac x = "f xb" in spec)
apply (drule_tac x = "g xb" in spec)
apply (drule bspec, assumption)
apply (blast intro: add_mono order_trans)
done

lemma Always_union:
     "[| F ∈ Always {s. f' s ≤ f s}; F ∈ Always {s. g' s ≤ g s} |]
      ==> F ∈ Always {s. f' s + g' s ≤ f s + (g s :: ('a::order) multiset)}"
apply (simp add: Always_eq_includes_reachable)
apply (blast intro: add_mono)
done


lemma Follows_union_lemma:
     "[| F ∈ Increasing f; F ∈ Increasing g;
         F ∈ Increasing g'; F ∈ Always {s. f' s ≤ f s};
         ∀k::('a::order) multiset.
           F ∈ {s. k ≤ f s} LeadsTo {s. k ≤ f' s} |]
      ==> F ∈ {s. k ≤ f s + g s} LeadsTo {s. k ≤ f' s + g s}"
apply (rule single_LeadsTo_I)
apply (drule_tac x = "f s" in IncreasingD)
apply (drule_tac x = "g s" in IncreasingD)
apply (rule LeadsTo_weaken)
apply (rule PSP_Stable)
apply (erule_tac x = "f s" in spec)
apply (erule Stable_Int, assumption, blast)
apply (blast intro: add_mono order_trans)
done
```

```
lemma Follows_union:
     "!!g g' ::'b => ('a::order) multiset.
        [| F ∈ f' Fols f;  F ∈ g' Fols g |]
        ==> F ∈ (%s. (f' s) + (g' s)) Fols (%s. (f s) + (g s))"
apply (simp add: Follows_def)
apply (simp add: Increasing_union Always_union, auto)
apply (rule LeadsTo_Trans)
apply (blast intro: Follows_union_lemma)

apply (simp add: union_commute)
apply (blast intro: Follows_union_lemma)
done

lemma Follows_sum:
     "!!f ::['c,'b] => ('a::order) multiset.
        [| ∀i ∈ I. F ∈ f' i Fols f i;  finite I |]
        ==> F ∈ (%s. ∑i ∈ I. f' i s) Fols (%s. ∑i ∈ I. f i s)"
apply (erule rev_mp)
apply (erule finite_induct, simp)
apply (simp add: Follows_union)
done



lemma Increasing_imp_Stable_pfixGe:
     "F ∈ Increasing func ==> F ∈ Stable {s. h pfixGe (func s)}"
apply (simp add: Increasing_def Stable_def Constrains_def constrains_def)
apply (blast intro: trans_Ge [THEN trans_genPrefix, THEN transD]
                    prefix_imp_pfixGe)
done


lemma LeadsTo_le_imp_pfixGe:
     "∀z. F ∈ {s. z ≤ f s} LeadsTo {s. z ≤ g s}
      ==> F ∈ {s. z pfixGe f s} LeadsTo {s. z pfixGe g s}"
apply (rule single_LeadsTo_I)
apply (drule_tac x = "f s" in spec)
apply (erule LeadsTo_weaken)
 prefer 2
 apply (blast intro: trans_Ge [THEN trans_genPrefix, THEN transD]
                     prefix_imp_pfixGe, blast)
done

end
```

15 Predicate Transformers

theory *Transformers* **imports** *Comp* **begin**

15.1 Defining the Predicate Transformers *wp*, *awp* and *wens*

definition *wp :: "[('a*'a) set, 'a set] => 'a set"* **where**
— Dijkstra's weakest-precondition operator (for an individual command)

```
"wp act B == - (act^-1 `` (-B))"
```

definition *awp :: "['a program, 'a set] => 'a set"* **where**
— Dijkstra's weakest-precondition operator (for a program)
"awp F B == (⋂act ∈ Acts F. wp act B)"

definition *wens :: "['a program, ('a*'a) set, 'a set] => 'a set"* **where**
— The weakest-ensures transformer
"wens F act B == gfp(λX. (wp act B ∩ awp F (B ∪ X)) ∪ B)"

The fundamental theorem for wp

theorem *wp_iff: "(A <= wp act B) = (act `` A <= B)"*
by *(force simp add: wp_def)*

This lemma is a good deal more intuitive than the definition!

lemma *in_wp_iff: "(a ∈ wp act B) = (∀x. (a,x) ∈ act --> x ∈ B)"*
by *(simp add: wp_def, blast)*

lemma *Compl_Domain_subset_wp: "- (Domain act) ⊆ wp act B"*
by *(force simp add: wp_def)*

lemma *wp_empty [simp]: "wp act {} = - (Domain act)"*
by *(force simp add: wp_def)*

The identity relation is the skip action

lemma *wp_Id [simp]: "wp Id B = B"*
by *(simp add: wp_def)*

lemma *wp_totalize_act:*
"wp (totalize_act act) B = (wp act B ∩ Domain act) ∪ (B - Domain act)"
by *(simp add: wp_def totalize_act_def, blast)*

lemma *awp_subset: "(awp F A ⊆ A)"*
by *(force simp add: awp_def wp_def)*

lemma *awp_Int_eq: "awp F (A∩B) = awp F A ∩ awp F B"*
by *(simp add: awp_def wp_def, blast)*

The fundamental theorem for awp

theorem *awp_iff_constrains: "(A <= awp F B) = (F ∈ A co B)"*
by *(simp add: awp_def constrains_def wp_iff INT_subset_iff)*

lemma *awp_iff_stable: "(A ⊆ awp F A) = (F ∈ stable A)"*
by *(simp add: awp_iff_constrains stable_def)*

lemma *stable_imp_awp_ident: "F ∈ stable A ==> awp F A = A"*
apply *(rule equalityI [OF awp_subset])*
apply *(simp add: awp_iff_stable)*
done

lemma *wp_mono: "(A ⊆ B) ==> wp act A ⊆ wp act B"*
by *(simp add: wp_def, blast)*

```
lemma awp_mono: "(A ⊆ B) ==> awp F A ⊆ awp F B"
by (simp add: awp_def wp_def, blast)

lemma wens_unfold:
     "wens F act B = (wp act B ∩ awp F (B ∪ wens F act B)) ∪ B"
apply (simp add: wens_def)
apply (rule gfp_unfold)
apply (simp add: mono_def wp_def awp_def, blast)
done

lemma wens_Id [simp]: "wens F Id B = B"
by (simp add: wens_def gfp_def wp_def awp_def, blast)
```

These two theorems justify the claim that *wens* returns the weakest assertion satisfying the ensures property

```
lemma ensures_imp_wens: "F ∈ A ensures B ==> ∃act ∈ Acts F. A ⊆ wens F
act B"
apply (simp add: wens_def ensures_def transient_def, clarify)
apply (rule rev_bexI, assumption)
apply (rule gfp_upperbound)
apply (simp add: constrains_def awp_def wp_def, blast)
done

lemma wens_ensures: "act ∈ Acts F ==> F ∈ (wens F act B) ensures B"
by (simp add: wens_def gfp_def constrains_def awp_def wp_def
              ensures_def transient_def, blast)
```

These two results constitute assertion (4.13) of the thesis

```
lemma wens_mono: "(A ⊆ B) ==> wens F act A ⊆ wens F act B"
apply (simp add: wens_def wp_def awp_def)
apply (rule gfp_mono, blast)
done

lemma wens_weakening: "B ⊆ wens F act B"
by (simp add: wens_def gfp_def, blast)
```

Assertion (6), or 4.16 in the thesis

```
lemma subset_wens: "A-B ⊆ wp act B ∩ awp F (B ∪ A) ==> A ⊆ wens F act
B"
apply (simp add: wens_def wp_def awp_def)
apply (rule gfp_upperbound, blast)
done
```

Assertion 4.17 in the thesis

```
lemma Diff_wens_constrains: "F ∈ (wens F act A - A) co wens F act A"
by (simp add: wens_def gfp_def wp_def awp_def constrains_def, blast)
```

— Proved instantly, yet remarkably fragile. If *Un_subset_iff* is declared as an iff-rule, then it's almost impossible to prove. One proof is via *meson* after expanding all definitions, but it's slow!

Assertion (7): 4.18 in the thesis. NOTE that many of these results hold for an arbitrary action. We often do not require *act ∈ Acts F*

```
lemma stable_wens: "F ∈ stable A ==> F ∈ stable (wens F act A)"
```

```
apply (simp add: stable_def)
apply (drule constrains_Un [OF Diff_wens_constrains [of F act A]])
apply (simp add: Un_Int_distrib2 Compl_partition2)
apply (erule constrains_weaken, blast)
apply (simp add: wens_weakening)
done
```

Assertion 4.20 in the thesis.

```
lemma wens_Int_eq_lemma:
      "[|T-B ⊆ awp F T; act ∈ Acts F|]
       ==> T ∩ wens F act B ⊆ wens F act (T∩B)"
apply (rule subset_wens)
apply (rule_tac P="λx. f x ⊆ b" for f b in ssubst [OF wens_unfold])
apply (simp add: wp_def awp_def, blast)
done
```

Assertion (8): 4.21 in the thesis. Here we indeed require `act ∈ Acts F`

```
lemma wens_Int_eq:
      "[|T-B ⊆ awp F T; act ∈ Acts F|]
       ==> T ∩ wens F act B = T ∩ wens F act (T∩B)"
apply (rule equalityI)
 apply (simp_all add: Int_lower1)
 apply (rule wens_Int_eq_lemma, assumption+)
apply (rule subset_trans [OF _ wens_mono [of "T∩B" B]], auto)
done
```

15.2 Defining the Weakest Ensures Set

```
inductive_set
  wens_set :: "['a program, 'a set] => 'a set set"
  for F :: "'a program" and B :: "'a set"
where

  Basis: "B ∈ wens_set F B"

| Wens:  "[|X ∈ wens_set F B; act ∈ Acts F|] ==> wens F act X ∈ wens_set
F B"

| Union: "W ≠ {} ==> ∀U ∈ W. U ∈ wens_set F B ==> ⋃W ∈ wens_set F B"

lemma wens_set_imp_co: "A ∈ wens_set F B ==> F ∈ (A-B) co A"
apply (erule wens_set.induct)
  apply (simp add: constrains_def)
 apply (drule_tac act1=act and A1=X
        in constrains_Un [OF Diff_wens_constrains])
 apply (erule constrains_weaken, blast)
 apply (simp add: wens_weakening)
apply (rule constrains_weaken)
apply (rule_tac I=W and A="λv. v-B" and A'="λv. v" in constrains_UN, blast+)
done

lemma wens_set_imp_leadsTo: "A ∈ wens_set F B ==> F ∈ A leadsTo B"
apply (erule wens_set.induct)
  apply (rule leadsTo_refl)
```

```
 apply (blast intro: wens_ensures leadsTo_Trans)
apply (blast intro: leadsTo_Union)
done

lemma leadsTo_imp_wens_set: "F ∈ A leadsTo B ==> ∃C ∈ wens_set F B. A ⊆
C"
apply (erule leadsTo_induct_pre)
  apply (blast dest!: ensures_imp_wens intro: wens_set.Basis wens_set.Wens)

 apply (clarify, drule ensures_weaken_R, assumption)
 apply (blast dest!: ensures_imp_wens intro: wens_set.Wens)
apply (case_tac "S={}")
 apply (simp, blast intro: wens_set.Basis)
apply (clarsimp dest!: bchoice simp: ball_conj_distrib Bex_def)
apply (rule_tac x = "⋃{Z. ∃U∈S. Z = f U}" in exI)
apply (blast intro: wens_set.Union)
done
```

Assertion (9): 4.27 in the thesis.

```
lemma leadsTo_iff_wens_set: "(F ∈ A leadsTo B) = (∃C ∈ wens_set F B. A ⊆
C)"
by (blast intro: leadsTo_imp_wens_set leadsTo_weaken_L wens_set_imp_leadsTo)
```

This is the result that requires the definition of `wens_set` to require `W` to be non-empty in the Unio case, for otherwise we should always have `{} ∈ wens_set F B`.

```
lemma wens_set_imp_subset: "A ∈ wens_set F B ==> B ⊆ A"
apply (erule wens_set.induct)
  apply (blast intro: wens_weakening [THEN subsetD])+
done
```

15.3 Properties Involving Program Union

Assertion (4.30) of thesis, reoriented

```
lemma awp_Join_eq: "awp (F⊔G) B = awp F B ∩ awp G B"
by (simp add: awp_def wp_def, blast)

lemma wens_subset: "wens F act B - B ⊆ wp act B ∩ awp F (B ∪ wens F act
B)"
by (subst wens_unfold, fast)
```

Assertion (4.31)

```
lemma subset_wens_Join:
      "[|A = T ∩ wens F act B;  T-B ⊆ awp F T; A-B ⊆ awp G (A ∪ B)|]
       ==> A ⊆ wens (F⊔G) act B"
apply (subgoal_tac "(T ∩ wens F act B) - B ⊆
                    wp act B ∩ awp F (B ∪ wens F act B) ∩ awp F T")
 apply (rule subset_wens)
 apply (simp add: awp_Join_eq awp_Int_eq Un_commute)
 apply (simp add: awp_def wp_def, blast)
apply (insert wens_subset [of F act B], blast)
done
```

Assertion (4.32)

```
lemma wens_Join_subset: "wens (F⊔G) act B ⊆ wens F act B"
apply (simp add: wens_def)
apply (rule gfp_mono)
apply (auto simp add: awp_Join_eq)
done
```

Lemma, because the inductive step is just too messy.

```
lemma wens_Union_inductive_step:
  assumes awpF: "T-B ⊆ awp F T"
      and awpG: "!!X. X ∈ wens_set F B ==> (T∩X) - B ⊆ awp G (T∩X)"
  shows "[|X ∈ wens_set F B; act ∈ Acts F; Y ⊆ X; T∩X = T∩Y|]
         ==> wens (F⊔G) act Y ⊆ wens F act X ∧
             T ∩ wens F act X = T ∩ wens (F⊔G) act Y"
apply (subgoal_tac "wens (F⊔G) act Y ⊆ wens F act X")
 prefer 2
 apply (blast dest: wens_mono intro: wens_Join_subset [THEN subsetD], simp)
apply (rule equalityI)
 prefer 2 apply blast
apply (simp add: Int_lower1)
apply (frule wens_set_imp_subset)
apply (subgoal_tac "T-X ⊆ awp F T")
 prefer 2 apply (blast intro: awpF [THEN subsetD])
apply (rule_tac B = "wens (F⊔G) act (T∩X)" in subset_trans)
 prefer 2 apply (blast intro!: wens_mono)
apply (subst wens_Int_eq, assumption+)
apply (rule subset_wens_Join [of _ T], simp, blast)
apply (subgoal_tac "T ∩ wens F act (T∩X) ∪ T∩X = T ∩ wens F act X")
 prefer 2
 apply (subst wens_Int_eq [symmetric], assumption+)
 apply (blast intro: wens_weakening [THEN subsetD], simp)
apply (blast intro: awpG [THEN subsetD] wens_set.Wens)
done

theorem wens_Union:
  assumes awpF: "T-B ⊆ awp F T"
      and awpG: "!!X. X ∈ wens_set F B ==> (T∩X) - B ⊆ awp G (T∩X)"
      and major: "X ∈ wens_set F B"
  shows "∃Y ∈ wens_set (F⊔G) B. Y ⊆ X & T∩X = T∩Y"
apply (rule wens_set.induct [OF major])
```

Basis: trivial

```
  apply (blast intro: wens_set.Basis)
```

Inductive step

```
 apply clarify
 apply (rule_tac x = "wens (F⊔G) act Y" in rev_bexI)
  apply (force intro: wens_set.Wens)
 apply (simp add: wens_Union_inductive_step [OF awpF awpG])
```

Union: by Axiom of Choice

```
apply (simp add: ball_conj_distrib Bex_def)
apply (clarify dest!: bchoice)
```

```
apply (rule_tac x = "⋃{Z. ∃U∈W. Z = f U}" in exI)
apply (blast intro: wens_set.Union)
done

theorem leadsTo_Join:
  assumes leadsTo: "F ∈ A leadsTo B"
      and awpF: "T-B ⊆ awp F T"
      and awpG: "!!X. X ∈ wens_set F B ==> (T∩X) - B ⊆ awp G (T∩X)"
  shows "F⊔G ∈ T∩A leadsTo B"
apply (rule leadsTo [THEN leadsTo_imp_wens_set, THEN bexE])
apply (rule wens_Union [THEN bexE])
   apply (rule awpF)
  apply (erule awpG, assumption)
apply (blast intro: wens_set_imp_leadsTo [THEN leadsTo_weaken_L])
done
```

15.4 The Set *wens_set F B* for a Single-Assignment Program

Thesis Section 4.3.3

We start by proving laws about single-assignment programs

```
lemma awp_single_eq [simp]:
     "awp (mk_program (init, {act}, allowed)) B = B ∩ wp act B"
by (force simp add: awp_def wp_def)

lemma wp_Un_subset: "wp act A ∪ wp act B ⊆ wp act (A ∪ B)"
by (force simp add: wp_def)

lemma wp_Un_eq: "single_valued act ==> wp act (A ∪ B) = wp act A ∪ wp act
B"
apply (rule equalityI)
 apply (force simp add: wp_def single_valued_def)
apply (rule wp_Un_subset)
done

lemma wp_UN_subset: "(⋃i∈I. wp act (A i)) ⊆ wp act (⋃i∈I. A i)"
by (force simp add: wp_def)

lemma wp_UN_eq:
     "[|single_valued act; I≠{}|]
      ==> wp act (⋃i∈I. A i) = (⋃i∈I. wp act (A i))"
apply (rule equalityI)
 prefer 2 apply (rule wp_UN_subset)
 apply (simp add: wp_def Image_INT_eq)
done

lemma wens_single_eq:
     "wens (mk_program (init, {act}, allowed)) act B = B ∪ wp act B"
by (simp add: wens_def gfp_def wp_def, blast)
```

Next, we express the *wens_set* for single-assignment programs

```
definition wens_single_finite :: "[('a*'a) set, 'a set, nat] => 'a set" where
```

```
    "wens_single_finite act B k == ⋃i ∈ atMost k. (wp act ^^ i) B"

definition wens_single :: "[('a*'a) set, 'a set] => 'a set" where
    "wens_single act B == ⋃i. (wp act ^^ i) B"

lemma wens_single_Un_eq:
      "single_valued act
       ==> wens_single act B ∪ wp act (wens_single act B) = wens_single act
B"
apply (rule equalityI)
 apply (simp_all add: Un_upper1)
apply (simp add: wens_single_def wp_UN_eq, clarify)
apply (rule_tac a="Suc xa" in UN_I, auto)
done

lemma atMost_nat_nonempty: "atMost (k::nat) ≠ {}"
by force

lemma wens_single_finite_0 [simp]: "wens_single_finite act B 0 = B"
by (simp add: wens_single_finite_def)

lemma wens_single_finite_Suc:
      "single_valued act
       ==> wens_single_finite act B (Suc k) =
           wens_single_finite act B k ∪ wp act (wens_single_finite act B k)"
apply (simp add: wens_single_finite_def wp_UN_eq [OF _ atMost_nat_nonempty])
apply (force elim!: le_SucE)
done

lemma wens_single_finite_Suc_eq_wens:
     "single_valued act
       ==> wens_single_finite act B (Suc k) =
           wens (mk_program (init, {act}, allowed)) act
                (wens_single_finite act B k)"
by (simp add: wens_single_finite_Suc wens_single_eq)

lemma def_wens_single_finite_Suc_eq_wens:
     "[|F = mk_program (init, {act}, allowed); single_valued act|]
       ==> wens_single_finite act B (Suc k) =
           wens F act (wens_single_finite act B k)"
by (simp add: wens_single_finite_Suc_eq_wens)

lemma wens_single_finite_Un_eq:
      "single_valued act
       ==> wens_single_finite act B k ∪ wp act (wens_single_finite act B k)
           ∈ range (wens_single_finite act B)"
by (simp add: wens_single_finite_Suc [symmetric])

lemma wens_single_eq_Union:
      "wens_single act B = ⋃(range (wens_single_finite act B))"
by (simp add: wens_single_finite_def wens_single_def, blast)

lemma wens_single_finite_eq_Union:
     "wens_single_finite act B n = (⋃k∈atMost n. wens_single_finite act B
```

```
k)"
apply (auto simp add: wens_single_finite_def)
apply (blast intro: le_trans)
done

lemma wens_single_finite_mono:
     "m ≤ n ==> wens_single_finite act B m ⊆ wens_single_finite act B n"
by (force simp add:  wens_single_finite_eq_Union [of act B n])

lemma wens_single_finite_subset_wens_single:
      "wens_single_finite act B k ⊆ wens_single act B"
by (simp add: wens_single_eq_Union, blast)

lemma subset_wens_single_finite:
      "[|W ⊆ wens_single_finite act B ` (atMost k); single_valued act; W≠{}|]
       ==> ∃m. ⋃W = wens_single_finite act B m"
apply (induct k)
 apply (rule_tac x=0 in exI, simp, blast)
apply (auto simp add: atMost_Suc)
apply (case_tac "wens_single_finite act B (Suc k) ∈ W")
 prefer 2 apply blast
apply (drule_tac x="Suc k" in spec)
apply (erule notE, rule equalityI)
 prefer 2 apply blast
apply (subst wens_single_finite_eq_Union)
apply (simp add: atMost_Suc, blast)
done
```

lemma for Union case

```
lemma Union_eq_wens_single:
      "⟦∀k. ¬ W ⊆ wens_single_finite act B ` {..k};
        W ⊆ insert (wens_single act B)
             (range (wens_single_finite act B))⟧
       ⟹ ⋃W = wens_single act B"
apply (cases "wens_single act B ∈ W")
 apply (blast dest: wens_single_finite_subset_wens_single [THEN subsetD])

apply (simp add: wens_single_eq_Union)
apply (rule equalityI, blast)
apply (simp add: UN_subset_iff, clarify)
apply (subgoal_tac "∃y∈W. ∃n. y = wens_single_finite act B n & i≤n")
 apply (blast intro: wens_single_finite_mono [THEN subsetD])
apply (drule_tac x=i in spec)
apply (force simp add: atMost_def)
done

lemma wens_set_subset_single:
      "single_valued act
       ==> wens_set (mk_program (init, {act}, allowed)) B ⊆
           insert (wens_single act B) (range (wens_single_finite act B))"
apply (rule subsetI)
apply (erule wens_set.induct)
```

Basis

```
  apply (fastforce simp add: wens_single_finite_def)
```

Wens inductive step

```
 apply (case_tac "acta = Id", simp)
 apply (simp add: wens_single_eq)
 apply (elim disjE)
 apply (simp add: wens_single_Un_eq)
 apply (force simp add: wens_single_finite_Un_eq)
```

Union inductive step

```
apply (case_tac "∃k. W ⊆ wens_single_finite act B ` (atMost k)")
 apply (blast dest!: subset_wens_single_finite, simp)
apply (rule disjI1 [OF Union_eq_wens_single], blast+)
done

lemma wens_single_finite_in_wens_set:
      "single_valued act ⟹
         wens_single_finite act B k
         ∈ wens_set (mk_program (init, {act}, allowed)) B"
apply (induct_tac k)
 apply (simp add: wens_single_finite_def wens_set.Basis)
apply (simp add: wens_set.Wens
                 wens_single_finite_Suc_eq_wens [of act B _ init allowed])

done

lemma single_subset_wens_set:
      "single_valued act
       ==> insert (wens_single act B) (range (wens_single_finite act B)) ⊆

           wens_set (mk_program (init, {act}, allowed)) B"
apply (simp add: image_def wens_single_eq_Union)
apply (blast intro: wens_set.Union wens_single_finite_in_wens_set)
done
```

Theorem (4.29)

```
theorem wens_set_single_eq:
     "[|F = mk_program (init, {act}, allowed); single_valued act|]
      ==> wens_set F B =
          insert (wens_single act B) (range (wens_single_finite act B))"
apply (rule equalityI)
 apply (simp add: wens_set_subset_single)
apply (erule ssubst, erule single_subset_wens_set)
done
```

Generalizing Misra's Fixed Point Union Theorem (4.41)

```
lemma fp_leadsTo_Join:
    "[|T-B ⊆ awp F T; T-B ⊆ FP G; F ∈ A leadsTo B|] ==> F⊔G ∈ T∩A leadsTo
B"
apply (rule leadsTo_Join, assumption, blast)
apply (simp add: FP_def awp_iff_constrains stable_def constrains_def, blast)

done
```

end

16 Progress Sets

theory *ProgressSets* **imports** *Transformers* **begin**

16.1 Complete Lattices and the Operator *cl*

definition *lattice :: "'a set set => bool"* **where**
— Meier calls them closure sets, but they are just complete lattices
"lattice L ==
(∀M. M ⊆ L --> ⋂M ∈ L) & (∀M. M ⊆ L --> ⋃M ∈ L)"

definition *cl :: "['a set set, 'a set] => 'a set"* **where**
— short for "closure"
"cl L r == ⋂{x. x∈L & r ⊆ x}"

lemma *UNIV_in_lattice: "lattice L ==> UNIV ∈ L"*
by *(force simp add: lattice_def)*

lemma *empty_in_lattice: "lattice L ==> {} ∈ L"*
by *(force simp add: lattice_def)*

lemma *Union_in_lattice: "[|M ⊆ L; lattice L|] ==> ⋃M ∈ L"*
by *(simp add: lattice_def)*

lemma *Inter_in_lattice: "[|M ⊆ L; lattice L|] ==> ⋂M ∈ L"*
by *(simp add: lattice_def)*

lemma *UN_in_lattice:*
"[|lattice L; !!i. i∈I ==> r i ∈ L|] ==> (⋃i∈I. r i) ∈ L"
apply *(blast intro: Union_in_lattice)*
done

lemma *INT_in_lattice:*
"[|lattice L; !!i. i∈I ==> r i ∈ L|] ==> (⋂i∈I. r i) ∈ L"
apply *(blast intro: Inter_in_lattice)*
done

lemma *Un_in_lattice: "[|x∈L; y∈L; lattice L|] ==> x∪y ∈ L"*
using *Union_in_lattice [of "{x, y}" L]* **by** *simp*

lemma *Int_in_lattice: "[|x∈L; y∈L; lattice L|] ==> x∩y ∈ L"*
using *Inter_in_lattice [of "{x, y}" L]* **by** *simp*

lemma *lattice_stable: "lattice {X. F ∈ stable X}"*
by *(simp add: lattice_def stable_def constrains_def, blast)*

The next three results state that *cl L r* is the minimal element of *L* that includes *r*.

lemma *cl_in_lattice: "lattice L ==> cl L r ∈ L"*
by *(simp add: lattice_def cl_def)*

lemma *cl_least: "[|c∈L; r⊆c|] ==> cl L r ⊆ c"*
by *(force simp add: cl_def)*

The next three lemmas constitute assertion (4.61)

lemma *cl_mono: "r ⊆ r' ==> cl L r ⊆ cl L r'"*
by *(simp add: cl_def, blast)*

lemma *subset_cl: "r ⊆ cl L r"*
by *(simp add: cl_def le_Inf_iff)*

A reformulation of *?r ⊆ cl ?L ?r*

lemma *clI: "x ∈ r ==> x ∈ cl L r"*
by *(simp add: cl_def, blast)*

A reformulation of $[\![?c \in ?L;\ ?r \subseteq ?c]\!] \Longrightarrow$ *cl ?L ?r ⊆ ?c*

lemma *clD: "[|c ∈ cl L r; B ∈ L; r ⊆ B|] ==> c ∈ B"*
by *(force simp add: cl_def)*

lemma *cl_UN_subset: "(⋃i∈I. cl L (r i)) ⊆ cl L (⋃i∈I. r i)"*
by *(simp add: cl_def, blast)*

lemma *cl_Un: "lattice L ==> cl L (r∪s) = cl L r ∪ cl L s"*
apply *(rule equalityI)*
prefer *2*
apply *(simp add: cl_def, blast)*
apply *(rule cl_least)*
apply *(blast intro: Un_in_lattice cl_in_lattice)*
apply *(blast intro: subset_cl [THEN subsetD])*
done

lemma *cl_UN: "lattice L ==> cl L (⋃i∈I. r i) = (⋃i∈I. cl L (r i))"*
apply *(rule equalityI)*
prefer *2* **apply** *(simp add: cl_def, blast)*
apply *(rule cl_least)*
apply *(blast intro: UN_in_lattice cl_in_lattice)*
apply *(blast intro: subset_cl [THEN subsetD])*
done

lemma *cl_Int_subset: "cl L (r∩s) ⊆ cl L r ∩ cl L s"*
by *(simp add: cl_def, blast)*

lemma *cl_idem [simp]: "cl L (cl L r) = cl L r"*
by *(simp add: cl_def, blast)*

lemma *cl_ident: "r∈L ==> cl L r = r"*
by *(force simp add: cl_def)*

lemma *cl_empty [simp]: "lattice L ==> cl L {} = {}"*
by *(simp add: cl_ident empty_in_lattice)*

lemma *cl_UNIV [simp]: "lattice L ==> cl L UNIV = UNIV"*
by *(simp add: cl_ident UNIV_in_lattice)*

Assertion (4.62)

```
lemma cl_ident_iff: "lattice L ==> (cl L r = r) = (r∈L)"
apply (rule iffI)
 apply (erule subst)
 apply (erule cl_in_lattice)
apply (erule cl_ident)
done

lemma cl_subset_in_lattice: "[|cl L r ⊆ r; lattice L|] ==> r∈L"
by (simp add: cl_ident_iff [symmetric] equalityI subset_cl)
```

16.2 Progress Sets and the Main Lemma

A progress set satisfies certain closure conditions and is a simple way of including the set `wens_set F B`.

```
definition closed :: "['a program, 'a set, 'a set,  'a set set] => bool" where
   "closed F T B L == ∀M. ∀act ∈ Acts F. B⊆M & T∩M ∈ L -->
                              T ∩ (B ∪ wp act M) ∈ L"

definition progress_set :: "['a program, 'a set, 'a set] => 'a set set set"
where
   "progress_set F T B ==
      {L. lattice L & B ∈ L & T ∈ L & closed F T B L}"

lemma closedD:
   "[|closed F T B L; act ∈ Acts F; B⊆M; T∩M ∈ L|]
    ==> T ∩ (B ∪ wp act M) ∈ L"
by (simp add: closed_def)
```

Note: the formalization below replaces Meier's `q` by `B` and `m` by `X`.

Part of the proof of the claim at the bottom of page 97. It's proved separately because the argument requires a generalization over all `act ∈ Acts F`.

```
lemma lattice_awp_lemma:
  assumes TXC:  "T∩X ∈ C" — induction hypothesis in theorem below
      and BsubX:  "B ⊆ X"   — holds in inductive step
      and latt: "lattice C"
      and TC:   "T ∈ C"
      and BC:   "B ∈ C"
      and clos: "closed F T B C"
    shows "T ∩ (B ∪ awp F (X ∪ cl C (T∩r))) ∈ C"
apply (simp del: INT_simps add: awp_def INT_extend_simps)
apply (rule INT_in_lattice [OF latt])
apply (erule closedD [OF clos])
apply (simp add: subset_trans [OF BsubX Un_upper1])
apply (subgoal_tac "T ∩ (X ∪ cl C (T∩r)) = (T∩X) ∪ cl C (T∩r)")
 prefer 2 apply (blast intro: TC clD)
apply (erule ssubst)
apply (blast intro: Un_in_lattice latt cl_in_lattice TXC)
done
```

Remainder of the proof of the claim at the bottom of page 97.

```
lemma lattice_lemma:
```

```
  assumes TXC:  "T∩X ∈ C" — induction hypothesis in theorem below
      and BsubX:  "B ⊆ X"   — holds in inductive step
      and act:  "act ∈ Acts F"
      and latt: "lattice C"
      and TC:   "T ∈ C"
      and BC:   "B ∈ C"
      and clos: "closed F T B C"
    shows "T ∩ (wp act X ∩ awp F (X ∪ cl C (T∩r)) ∪ X) ∈ C"
apply (subgoal_tac "T ∩ (B ∪ wp act X) ∈ C")
 prefer 2 apply (simp add: closedD [OF clos] act BsubX TXC)
apply (drule Int_in_lattice
             [OF _ lattice_awp_lemma [OF TXC BsubX latt TC BC clos, of r]
                  latt])
apply (subgoal_tac
         "T ∩ (B ∪ wp act X) ∩ (T ∩ (B ∪ awp F (X ∪ cl C (T∩r)))) =
          T ∩ (B ∪ wp act X ∩ awp F (X ∪ cl C (T∩r)))")
 prefer 2 apply blast
apply simp
apply (drule Un_in_lattice [OF _ TXC latt])
apply (subgoal_tac
         "T ∩ (B ∪ wp act X ∩ awp F (X ∪ cl C (T∩r))) ∪ T∩X =
          T ∩ (wp act X ∩ awp F (X ∪ cl C (T∩r)) ∪ X)")
 apply simp
apply (blast intro: BsubX [THEN subsetD])
done
```

Induction step for the main lemma

```
lemma progress_induction_step:
  assumes TXC:  "T∩X ∈ C" — induction hypothesis in theorem below
      and act:  "act ∈ Acts F"
      and Xwens: "X ∈ wens_set F B"
      and latt: "lattice C"
      and  TC:  "T ∈ C"
      and  BC:  "B ∈ C"
      and clos: "closed F T B C"
      and Fstable: "F ∈ stable T"
  shows "T ∩ wens F act X ∈ C"
proof -
  from Xwens have BsubX: "B ⊆ X"
    by (rule wens_set_imp_subset)
  let ?r = "wens F act X"
  have "?r ⊆ (wp act X ∩ awp F (X∪?r)) ∪ X"
    by (simp add: wens_unfold [symmetric])
  then have "T∩?r ⊆ T ∩ ((wp act X ∩ awp F (X∪?r)) ∪ X)"
    by blast
  then have "T∩?r ⊆ T ∩ ((wp act X ∩ awp F (T ∩ (X∪?r))) ∪ X)"
    by (simp add: awp_Int_eq Fstable stable_imp_awp_ident, blast)
  then have "T∩?r ⊆ T ∩ ((wp act X ∩ awp F (X ∪ cl C (T∩?r))) ∪ X)"
    by (blast intro: awp_mono [THEN [2] rev_subsetD] subset_cl [THEN subsetD])
  then have "cl C (T∩?r) ⊆
             cl C (T ∩ ((wp act X ∩ awp F (X ∪ cl C (T∩?r))) ∪ X))"
    by (rule cl_mono)
  then have "cl C (T∩?r) ⊆
             T ∩ ((wp act X ∩ awp F (X ∪ cl C (T∩?r))) ∪ X)"
```

```
    by (simp add: cl_ident lattice_lemma [OF TXC BsubX act latt TC BC clos])
  then have "cl C (T∩?r) ⊆ (wp act X ∩ awp F (X ∪ cl C (T∩?r))) ∪ X"
    by blast
  then have "cl C (T∩?r) ⊆ ?r"
    by (blast intro!: subset_wens)
  then have cl_subset: "cl C (T∩?r) ⊆ T∩?r"
    by (simp add: cl_ident TC
                  subset_trans [OF cl_mono [OF Int_lower1]])
  show ?thesis
    by (rule cl_subset_in_lattice [OF cl_subset latt])
qed
```

Proved on page 96 of Meier's thesis. The special case when `T = UNIV` states that every progress set for the program `F` and set `B` includes the set `wens_set F B`.

```
lemma progress_set_lemma:
     "[|C ∈ progress_set F T B; r ∈ wens_set F B; F ∈ stable T|] ==> T∩r
∈ C"
apply (simp add: progress_set_def, clarify)
apply (erule wens_set.induct)
```

Base

```
  apply (simp add: Int_in_lattice)
```

The difficult `wens` case

```
 apply (simp add: progress_induction_step)
```

Disjunctive case

```
apply (subgoal_tac "(⋃U∈W. T ∩ U) ∈ C")
 apply simp
apply (blast intro: UN_in_lattice)
done
```

16.3 The Progress Set Union Theorem

```
lemma closed_mono:
  assumes BB':  "B ⊆ B'"
      and TBwp: "T ∩ (B ∪ wp act M) ∈ C"
      and B'C:  "B' ∈ C"
      and TC:   "T ∈ C"
      and latt: "lattice C"
  shows "T ∩ (B' ∪ wp act M) ∈ C"
proof -
  from TBwp have "(T∩B) ∪ (T ∩ wp act M) ∈ C"
    by (simp add: Int_Un_distrib)
  then have TBBC: "(T∩B') ∪ ((T∩B) ∪ (T ∩ wp act M)) ∈ C"
    by (blast intro: Int_in_lattice Un_in_lattice TC B'C latt)
  show ?thesis
    by (rule eqelem_imp_iff [THEN iffD1, OF _ TBBC],
        blast intro: BB' [THEN subsetD])
qed


lemma progress_set_mono:
```

```
    assumes BB': "B ⊆ B'"
    shows
     "[| B' ∈ C;  C ∈ progress_set F T B|]
      ==> C ∈ progress_set F T B'"
by (simp add: progress_set_def closed_def closed_mono [OF BB']
              subset_trans [OF BB'])

theorem progress_set_Union:
  assumes leadsTo: "F ∈ A leadsTo B'"
      and prog: "C ∈ progress_set F T B"
      and Fstable: "F ∈ stable T"
      and BB': "B ⊆ B'"
      and B'C: "B' ∈ C"
      and Gco: "!!X. X∈C ==> G ∈ X-B co X"
  shows "F⊔G ∈ T∩A leadsTo B'"
apply (insert prog Fstable)
apply (rule leadsTo_Join [OF leadsTo])
  apply (force simp add: progress_set_def awp_iff_stable [symmetric])
apply (simp add: awp_iff_constrains)
apply (drule progress_set_mono [OF BB' B'C])
apply (blast intro: progress_set_lemma Gco constrains_weaken_L
                    BB' [THEN subsetD])
done
```

16.4 Some Progress Sets

```
lemma UNIV_in_progress_set: "UNIV ∈ progress_set F T B"
by (simp add: progress_set_def lattice_def closed_def)
```

16.4.1 Lattices and Relations

From Meier's thesis, section 4.5.3

```
definition relcl :: "'a set set => ('a * 'a) set" where
    — Derived relation from a lattice
    "relcl L == {(x,y). y ∈ cl L {x}}"

definition latticeof :: "('a * 'a) set => 'a set set" where
    — Derived lattice from a relation: the set of upwards-closed sets
    "latticeof r == {X. ∀s t. s ∈ X & (s,t) ∈ r --> t ∈ X}"


lemma relcl_refl: "(a,a) ∈ relcl L"
by (simp add: relcl_def subset_cl [THEN subsetD])

lemma relcl_trans:
     "[| (a,b) ∈ relcl L; (b,c) ∈ relcl L; lattice L |] ==> (a,c) ∈ relcl
L"
apply (simp add: relcl_def)
apply (blast intro: clD cl_in_lattice)
done

lemma refl_relcl: "lattice L ==> refl (relcl L)"
by (simp add: refl_onI relcl_def subset_cl [THEN subsetD])
```

```
lemma trans_relcl: "lattice L ==> trans (relcl L)"
by (blast intro: relcl_trans transI)

lemma lattice_latticeof: "lattice (latticeof r)"
by (auto simp add: lattice_def latticeof_def)

lemma lattice_singletonI:
     "[|lattice L; !!s. s ∈ X ==> {s} ∈ L|] ==> X ∈ L"
apply (cut_tac UN_singleton [of X])
apply (erule subst)
apply (simp only: UN_in_lattice)
done
```

Equation (4.71) of Meier's thesis. He gives no proof.

```
lemma cl_latticeof:
     "[|refl r; trans r|]
      ==> cl (latticeof r) X = {t. ∃s. s∈X & (s,t) ∈ r}"
apply (rule equalityI)
 apply (rule cl_least)
  apply (simp (no_asm_use) add: latticeof_def trans_def, blast)
 apply (simp add: latticeof_def refl_on_def, blast)
apply (simp add: latticeof_def, clarify)
apply (unfold cl_def, blast)
done
```

Related to (4.71).

```
lemma cl_eq_Collect_relcl:
     "lattice L ==> cl L X = {t. ∃s. s∈X & (s,t) ∈ relcl L}"
apply (cut_tac UN_singleton [of X])
apply (erule subst)
apply (force simp only: relcl_def cl_UN)
done
```

Meier's theorem of section 4.5.3

```
theorem latticeof_relcl_eq: "lattice L ==> latticeof (relcl L) = L"
apply (rule equalityI)
 prefer 2 apply (force simp add: latticeof_def relcl_def cl_def, clarify)

apply (rename_tac X)
apply (rule cl_subset_in_lattice)
 prefer 2 apply assumption
apply (drule cl_ident_iff [OF lattice_latticeof, THEN iffD2])
apply (drule equalityD1)
apply (rule subset_trans)
 prefer 2 apply assumption
apply (thin_tac "_ ⊆ X")
apply (cut_tac A=X in UN_singleton)
apply (erule subst)
apply (simp only: cl_UN lattice_latticeof
                  cl_latticeof [OF refl_relcl trans_relcl])
apply (simp add: relcl_def)
done
```

```
theorem relcl_latticeof_eq:
     "[|refl r; trans r|] ==> relcl (latticeof r) = r"
by (simp add: relcl_def cl_latticeof)
```

16.4.2 Decoupling Theorems

```
definition decoupled :: "['a program, 'a program] => bool" where
   "decoupled F G ==
        ∀act ∈ Acts F. ∀B. G ∈ stable B --> G ∈ stable (wp act B)"
```

Rao's Decoupling Theorem

```
lemma stableco: "F ∈ stable A ==> F ∈ A-B co A"
by (simp add: stable_def constrains_def, blast)

theorem decoupling:
  assumes leadsTo: "F ∈ A leadsTo B"
      and Gstable: "G ∈ stable B"
      and dec:     "decoupled F G"
  shows "F⊔G ∈ A leadsTo B"
proof -
  have prog: "{X. G ∈ stable X} ∈ progress_set F UNIV B"
    by (simp add: progress_set_def lattice_stable Gstable closed_def
                  stable_Un [OF Gstable] dec [unfolded decoupled_def])
  have "F⊔G ∈ (UNIV∩A) leadsTo B"
    by (rule progress_set_Union [OF leadsTo prog],
        simp_all add: Gstable stableco)
  thus ?thesis by simp
qed
```

Rao's Weak Decoupling Theorem

```
theorem weak_decoupling:
  assumes leadsTo: "F ∈ A leadsTo B"
      and stable: "F⊔G ∈ stable B"
      and dec:     "decoupled F (F⊔G)"
  shows "F⊔G ∈ A leadsTo B"
proof -
  have prog: "{X. F⊔G ∈ stable X} ∈ progress_set F UNIV B"
    by (simp del: Join_stable
             add: progress_set_def lattice_stable stable closed_def
                  stable_Un [OF stable] dec [unfolded decoupled_def])
  have "F⊔G ∈ (UNIV∩A) leadsTo B"
    by (rule progress_set_Union [OF leadsTo prog],
        simp_all del: Join_stable add: stable,
        simp add: stableco)
  thus ?thesis by simp
qed
```

The "Decoupling via *G'* Union Theorem"

```
theorem decoupling_via_aux:
  assumes leadsTo: "F ∈ A leadsTo B"
      and prog: "{X. G' ∈ stable X} ∈ progress_set F UNIV B"
      and GG':  "G ≤ G'"
```

— Beware! This is the converse of the refinement relation!

```
  shows "F⊔G ∈ A leadsTo B"
proof -
  from prog have stable: "G' ∈ stable B"
    by (simp add: progress_set_def)
  have "F⊔G ∈ (UNIV∩A) leadsTo B"
    by (rule progress_set_Union [OF leadsTo prog],
        simp_all add: stable stableco component_stable [OF GG'])
  thus ?thesis by simp
qed
```

16.5 Composition Theorems Based on Monotonicity and Commutativity

16.5.1 Commutativity of `cl L` and assignment.

```
definition commutes :: "['a program, 'a set, 'a set,  'a set set] => bool"
where
   "commutes F T B L ==
       ∀M. ∀act ∈ Acts F. B ⊆ M -->
           cl L (T ∩ wp act M) ⊆ T ∩ (B ∪ wp act (cl L (T∩M)))"
```

From Meier's thesis, section 4.5.6

```
lemma commutativity1_lemma:
  assumes commutes: "commutes F T B L"
      and lattice:  "lattice L"
      and BL: "B ∈ L"
      and TL: "T ∈ L"
  shows "closed F T B L"
apply (simp add: closed_def, clarify)
apply (rule ProgressSets.cl_subset_in_lattice [OF _ lattice])
apply (simp add: Int_Un_distrib cl_Un [OF lattice]
                 cl_ident Int_in_lattice [OF TL BL lattice] Un_upper1)
apply (subgoal_tac "cl L (T ∩ wp act M) ⊆ T ∩ (B ∪ wp act (cl L (T ∩ M)))")

 prefer 2
 apply (cut_tac commutes, simp add: commutes_def)
apply (erule subset_trans)
apply (simp add: cl_ident)
apply (blast intro: rev_subsetD [OF _ wp_mono])
done
```

Version packaged with ⟦?F ∈ ?A ⟼ ?B'; ?C ∈ progress_set ?F ?T ?B; ?F ∈ UNITY.stable ?T; ?B ⊆ ?B'; ?B' ∈ ?C; ⋀X. X ∈ ?C ⟹ ?G ∈ X - ?B co X⟧ ⟹ ?F ⊔ ?G ∈ ?T ∩ ?A ⟼ ?B'

```
lemma commutativity1:
  assumes leadsTo: "F ∈ A leadsTo B"
      and lattice:  "lattice L"
      and BL: "B ∈ L"
      and TL: "T ∈ L"
      and Fstable: "F ∈ stable T"
      and Gco: "!!X. X∈L ==> G ∈ X-B co X"
      and commutes: "commutes F T B L"
  shows "F⊔G ∈ T∩A leadsTo B"
by (rule progress_set_Union [OF leadsTo _ Fstable subset_refl BL Gco],
```

```
    simp add: progress_set_def commutativity1_lemma commutes lattice BL TL)
```

Possibly move to Relation.thy, after *single_valued*

```
definition funof :: "[('a*'b)set, 'a] => 'b" where
   "funof r == (λx. THE y. (x,y) ∈ r)"

lemma funof_eq: "[|single_valued r; (x,y) ∈ r|] ==> funof r x = y"
by (simp add: funof_def single_valued_def, blast)

lemma funof_Pair_in:
     "[|single_valued r; x ∈ Domain r|] ==> (x, funof r x) ∈ r"
by (force simp add: funof_eq)

lemma funof_in:
     "[|r``{x} ⊆ A; single_valued r; x ∈ Domain r|] ==> funof r x ∈ A"
by (force simp add: funof_eq)

lemma funof_imp_wp: "[|funof act t ∈ A; single_valued act|] ==> t ∈ wp act
A"
by (force simp add: in_wp_iff funof_eq)
```

16.5.2 Commutativity of Functions and Relation

Thesis, page 109

From Meier's thesis, section 4.5.6

```
lemma commutativity2_lemma:
  assumes dcommutes:
      "⋀act s t. act ∈ Acts F ⟹ s ∈ T ⟹ (s, t) ∈ relcl L ⟹
        s ∈ B | t ∈ B | (funof act s, funof act t) ∈ relcl L"
    and determ: "!!act. act ∈ Acts F ==> single_valued act"
    and total: "!!act. act ∈ Acts F ==> Domain act = UNIV"
    and lattice:  "lattice L"
    and BL: "B ∈ L"
    and TL: "T ∈ L"
    and Fstable: "F ∈ stable T"
  shows  "commutes F T B L"
proof -
  { fix M and act and t
    assume 1: "B ⊆ M" "act ∈ Acts F" "t ∈ cl L (T ∩ wp act M)"
    then have "∃s. (s,t) ∈ relcl L ∧ s ∈ T ∩ wp act M"
      by (force simp add: cl_eq_Collect_relcl [OF lattice])
    then obtain s where 2: "(s, t) ∈ relcl L" "s ∈ T" "s ∈ wp act M"
      by blast
    then have 3: "∀u∈L. s ∈ u --> t ∈ u"
      apply (intro ballI impI)
      apply (subst cl_ident [symmetric], assumption)
      apply (simp add: relcl_def)
      apply (blast intro: cl_mono [THEN [2] rev_subsetD])
      done
    with 1 2 Fstable have 4: "funof act s ∈ T∩M"
      by (force intro!: funof_in
        simp add: wp_def stable_def constrains_def determ total)
```

```
    with 1 2 3 have 5: "s ∈ B | t ∈ B | (funof act s, funof act t) ∈ relcl
L"
      by (intro dcommutes) assumption+
    with 1 2 3 4 have "t ∈ B | funof act t ∈ cl L (T∩M)"
      by (simp add: relcl_def) (blast intro: BL cl_mono [THEN [2] rev_subsetD])

    with 1 2 3 4 5 have "t ∈ B | t ∈ wp act (cl L (T∩M))"
      by (blast intro: funof_imp_wp determ)
    with 2 3 have "t ∈ T ∧ (t ∈ B ∨ t ∈ wp act (cl L (T ∩ M)))"
      by (blast intro: TL cl_mono [THEN [2] rev_subsetD])
    then have"t ∈ T ∩ (B ∪ wp act (cl L (T ∩ M)))"
      by simp
  }
  then show "commutes F T B L" unfolding commutes_def by clarify
qed
```

Version packaged with $[\![?F \in ?A \longmapsto ?B'; ?C \in progress\_set\ ?F\ ?T\ ?B; ?F \in UNITY.stable\ ?T; ?B \subseteq ?B'; ?B' \in ?C; \bigwedge X.\ X \in ?C \Longrightarrow ?G \in X - ?B\ co\ X]\!] \Longrightarrow ?F \sqcup ?G \in ?T \cap ?A \longmapsto ?B'$

```
lemma commutativity2:
  assumes leadsTo: "F ∈ A leadsTo B"
      and dcommutes:
        "∀act ∈ Acts F.
         ∀s ∈ T. ∀t. (s,t) ∈ relcl L -->
                     s ∈ B | t ∈ B | (funof act s, funof act t) ∈ relcl
L"
      and determ: "!!act. act ∈ Acts F ==> single_valued act"
      and total: "!!act. act ∈ Acts F ==> Domain act = UNIV"
      and lattice:  "lattice L"
      and BL: "B ∈ L"
      and TL: "T ∈ L"
      and Fstable: "F ∈ stable T"
      and Gco: "!!X. X∈L ==> G ∈ X-B co X"
  shows "F⊔G ∈ T∩A leadsTo B"
apply (rule commutativity1 [OF leadsTo lattice])
apply (simp_all add: Gco commutativity2_lemma dcommutes determ total
                     lattice BL TL Fstable)
done
```

16.6 Monotonicity

From Meier's thesis, section 4.5.7, page 110

```
end
```

17 Comprehensive UNITY Theory

```
theory UNITY_Main
imports Detects PPROD Follows ProgressSets
begin

ML_file ‹UNITY_tactics.ML›
```

```
method_setup safety = ‹
    Scan.succeed (SIMPLE_METHOD' o constrains_tac)›
    "for proving safety properties"

method_setup ensures_tac = ‹
  Args.goal_spec -- Scan.lift Parse.embedded_inner_syntax >>
  (fn (quant, s) => fn ctxt => SIMPLE_METHOD'' quant (ensures_tac ctxt s))
› "for proving progress properties"

setup ‹
  map_theory_simpset (fn ctxt => ctxt
    addsimps (make_o_equivs ctxt @{thm fst_o_funPair} @ make_o_equivs ctxt
@{thm snd_o_funPair})
    addsimps (make_o_equivs ctxt @{thm fst_o_lift_map} @ make_o_equivs ctxt
@{thm snd_o_lift_map}))
›

end


theory Deadlock imports "../UNITY" begin


lemma "[| F ∈ (A ∩ B) co A;  F ∈ (B ∩ A) co B |] ==> F ∈ stable (A ∩ B)"
  unfolding constrains_def stable_def by blast



lemma Collect_le_Int_equals:
     "(⋂i ∈ atMost n. A(Suc i) ∩ A i) = (⋂i ∈ atMost (Suc n). A i)"
  by (induct n) (auto simp add: atMost_Suc)


lemma UN_Int_Compl_subset:
     "(⋃i ∈ lessThan n. A i) ∩ (- A n) ⊆
      (⋃i ∈ lessThan n. (A i) ∩ (- A (Suc i)))"
  by (induct n) (auto simp: lessThan_Suc)



lemma INT_Un_Compl_subset:
     "(⋂i ∈ lessThan n. -A i ∪ A (Suc i))  ⊆
      (⋂i ∈ lessThan n. -A i) ∪ A n"
  by (induct n) (auto simp: lessThan_Suc)



lemma INT_le_equals_Int_lemma:
     "A 0 ∩ (-(A n) ∩ (⋂i ∈ lessThan n. -A i ∪ A (Suc i))) = {}"
by (blast intro: gr0I dest: INT_Un_Compl_subset [THEN subsetD])


lemma INT_le_equals_Int:
     "(⋂i ∈ atMost n. A i) =
```

```
      A 0 ∩ (⋂i ∈ lessThan n. -A i ∪ A(Suc i))"
  by (induct n)
    (simp_all add: Int_ac Int_Un_distrib Int_Un_distrib2
      INT_le_equals_Int_lemma lessThan_Suc atMost_Suc)

lemma INT_le_Suc_equals_Int:
     "(⋂i ∈ atMost (Suc n). A i) =
      A 0 ∩ (⋂i ∈ atMost n. -A i ∪ A(Suc i))"
by (simp add: lessThan_Suc_atMost INT_le_equals_Int)



lemma
  assumes zeroprem: "F ∈ (A 0 ∩ A (Suc n)) co (A 0)"
      and allprem:
            "!!i. i ∈ atMost n ==> F ∈ (A(Suc i) ∩ A i) co (-A i ∪ A(Suc
i))"
  shows "F ∈ stable (⋂i ∈ atMost (Suc n). A i)"
apply (unfold stable_def)
apply (rule constrains_Int [THEN constrains_weaken])
   apply (rule zeroprem)
  apply (rule constrains_INT)
  apply (erule allprem)
 apply (simp add: Collect_le_Int_equals Int_assoc INT_absorb)
apply (simp add: INT_le_Suc_equals_Int)
done

end


theory Common
imports "../UNITY_Main"
begin

consts
  ftime :: "nat=>nat"
  gtime :: "nat=>nat"

axiomatization where
  fmono: "m ≤ n ==> ftime m ≤ ftime n" and
  gmono: "m ≤ n ==> gtime m ≤ gtime n" and

  fasc:  "m ≤ ftime n" and
  gasc:  "m ≤ gtime n"

definition common :: "nat set" where
    "common == {n. ftime n = n & gtime n = n}"

definition maxfg :: "nat => nat set" where
    "maxfg m == {t. t ≤ max (ftime m) (gtime m)}"



lemma common_stable:
```

```
     "[| ∀m. F ∈ {m} Co (maxfg m); n ∈ common |]
      ==> F ∈ Stable (atMost n)"
apply (drule_tac M = "{t. t ≤ n}" in Elimination_sing)
apply (simp add: atMost_def Stable_def common_def maxfg_def le_max_iff_disj)
apply (erule Constrains_weaken_R)
apply (blast intro: order_eq_refl le_trans dest: fmono gmono)
done

lemma common_safety:
     "[| Init F ⊆ atMost n;
         ∀m. F ∈ {m} Co (maxfg m); n ∈ common |]
      ==> F ∈ Always (atMost n)"
by (simp add: AlwaysI common_stable)



lemma "SKIP ∈ {m} co (maxfg m)"
by (simp add: constrains_def maxfg_def le_max_iff_disj fasc)


lemma "mk_total_program
         (UNIV, {range(%t.(t,ftime t)), range(%t.(t,gtime t))}, UNIV)
       ∈ {m} co (maxfg m)"
apply (simp add: mk_total_program_def)
apply (simp add: constrains_def maxfg_def le_max_iff_disj fasc)
done


lemma "mk_total_program (UNIV, {range(%t.(t, max (ftime t) (gtime t)))},
UNIV)
       ∈ {m} co (maxfg m)"
apply (simp add: mk_total_program_def)
apply (simp add: constrains_def maxfg_def gasc max.absorb2)
done


lemma  "mk_total_program
          (UNIV, { {(t, Suc t) | t. t < max (ftime t) (gtime t)} }, UNIV)
       ∈ {m} co (maxfg m)"
apply (simp add: mk_total_program_def)
apply (simp add: constrains_def maxfg_def gasc max.absorb2)
done




lemma leadsTo_common_lemma:
  assumes "∀m. F ∈ {m} Co (maxfg m)"
    and "∀m ∈ lessThan n. F ∈ {m} LeadsTo (greaterThan m)"
    and "n ∈ common"
```

```
  shows "F ∈ (atMost n) LeadsTo common"
proof (rule LeadsTo_weaken_R)
  show "F ∈ {..n} LeadsTo {..n} ∩ id -‘ {n..} ∪ common"
  proof (induct rule: GreaterThan_bounded_induct [of n _ _ id])
    case 1
    from assms have "∀m∈{..<n}. F ∈ {..n} ∩ {m} LeadsTo {..n} ∩ {m<..}
∪ common"
      by (blast dest: PSP_Stable2 intro: common_stable LeadsTo_weaken_R)
    then show ?case by simp
  qed
next
  from ‹n ∈ common›
  show "{..n} ∩ id -‘ {n..} ∪ common ⊆ common"
    by (simp add: atMost_Int_atLeast)
qed


lemma leadsTo_common:
     "[| ∀m. F ∈ {m} Co (maxfg m);
         ∀m ∈ -common. F ∈ {m} LeadsTo (greaterThan m);
         n ∈ common |]
      ==> F ∈ (atMost (LEAST n. n ∈ common)) LeadsTo common"
apply (rule leadsTo_common_lemma)
apply (simp_all (no_asm_simp))
apply (erule_tac [2] LeastI)
apply (blast dest!: not_less_Least)
done

end


theory Network imports "../UNITY" begin



datatype pvar = Sent | Rcvd | Idle

datatype pname = Aproc | Bproc

type_synonym state = "pname * pvar => nat"

locale F_props =
  fixes F
  assumes rsA: "F ∈ stable {s. s(Bproc,Rcvd) ≤ s(Aproc,Sent)}"
      and rsB: "F ∈ stable {s. s(Aproc,Rcvd) ≤ s(Bproc,Sent)}"
    and sent_nondec: "F ∈ stable {s. m ≤ s(proc,Sent)}"
    and rcvd_nondec: "F ∈ stable {s. n ≤ s(proc,Rcvd)}"
    and rcvd_idle: "F ∈ {s. s(proc,Idle) = Suc 0 & s(proc,Rcvd) = m}
                        co {s. s(proc,Rcvd) = m --> s(proc,Idle) = Suc 0}"
    and sent_idle: "F ∈ {s. s(proc,Idle) = Suc 0 & s(proc,Sent) = n}
                        co {s. s(proc,Sent) = n}"
begin

lemmas sent_nondec_A = sent_nondec [of _ Aproc]
```

```
    and sent_nondec_B = sent_nondec [of _ Bproc]
    and rcvd_nondec_A = rcvd_nondec [of _ Aproc]
    and rcvd_nondec_B = rcvd_nondec [of _ Bproc]
    and rcvd_idle_A = rcvd_idle [of Aproc]
    and rcvd_idle_B = rcvd_idle [of Bproc]
    and sent_idle_A = sent_idle [of Aproc]
    and sent_idle_B = sent_idle [of Bproc]

    and rs_AB = stable_Int [OF rsA rsB]

lemmas sent_nondec_AB = stable_Int [OF sent_nondec_A sent_nondec_B]
    and rcvd_nondec_AB = stable_Int [OF rcvd_nondec_A rcvd_nondec_B]
    and rcvd_idle_AB = constrains_Int [OF rcvd_idle_A rcvd_idle_B]
    and sent_idle_AB = constrains_Int [OF sent_idle_A sent_idle_B]

lemmas nondec_AB = stable_Int [OF sent_nondec_AB rcvd_nondec_AB]
    and idle_AB = constrains_Int [OF rcvd_idle_AB sent_idle_AB]

lemmas nondec_idle = constrains_Int [OF nondec_AB [unfolded stable_def] idle_AB]

lemma
  shows "F ∈ stable {s. s(Aproc,Idle) = Suc 0 & s(Bproc,Idle) = Suc 0 &
                        s(Aproc,Sent) = s(Bproc,Rcvd) &
                        s(Bproc,Sent) = s(Aproc,Rcvd) &
                        s(Aproc,Rcvd) = m & s(Bproc,Rcvd) = n}"
apply (unfold stable_def)
apply (rule constrainsI)
apply (drule constrains_Int [OF rs_AB [unfolded stable_def] nondec_idle,
                             THEN constrainsD], assumption)
apply simp_all
apply (blast del: le0, clarify)
apply (subgoal_tac "s' (Aproc, Rcvd) = s (Aproc, Rcvd)")
apply (subgoal_tac "s' (Bproc, Rcvd) = s (Bproc, Rcvd)")
apply simp
apply (blast intro: order_antisym le_trans eq_imp_le)+
done

end

end
```

18 The Token Ring

```
theory Token
imports "../WFair"

begin
```

From Misra, "A Logic for Concurrent Programming" (1994), sections 5.2 and 13.2.

18.1 Definitions

datatype *pstate = Hungry | Eating | Thinking*
— process states

record *state =*
token :: "nat"
proc :: "nat => pstate"

definition *HasTok :: "nat => state set"* **where**
"HasTok i == {s. token s = i}"

definition *H :: "nat => state set"* **where**
"H i == {s. proc s i = Hungry}"

definition *E :: "nat => state set"* **where**
"E i == {s. proc s i = Eating}"

definition *T :: "nat => state set"* **where**
"T i == {s. proc s i = Thinking}"

locale *Token =*
fixes *N* **and** *F* **and** *nodeOrder* **and** *"next"*
defines *nodeOrder_def:*
"nodeOrder j == measure(%i. ((j+N)-i) mod N) ∩ {..<N} × {..<N}"
and *next_def:*
"next i == (Suc i) mod N"
assumes *N_positive [iff]: "0<N"*
and *TR2: "F ∈ (T i) co (T i ∪ H i)"*
and *TR3: "F ∈ (H i) co (H i ∪ E i)"*
and *TR4: "F ∈ (H i - HasTok i) co (H i)"*
and *TR5: "F ∈ (HasTok i) co (HasTok i ∪ -(E i))"*
and *TR6: "F ∈ (H i ∩ HasTok i) leadsTo (E i)"*
and *TR7: "F ∈ (HasTok i) leadsTo (HasTok (next i))"*

lemma *HasToK_partition: "[| s ∈ HasTok i; s ∈ HasTok j |] ==> i=j"*
by *(unfold HasTok_def, auto)*

lemma *not_E_eq: "(s ∉ E i) = (s ∈ H i | s ∈ T i)"*
apply *(simp add: H_def E_def T_def)*
apply *(cases "proc s i", auto)*
done

context *Token*
begin

lemma *token_stable: "F ∈ stable (-(E i) ∪ (HasTok i))"*
apply *(unfold stable_def)*
apply *(rule constrains_weaken)*
apply *(rule constrains_Un [OF constrains_Un [OF TR2 TR4] TR5])*
apply *(auto simp add: not_E_eq)*

```
apply (simp_all add: H_def E_def T_def)
done
```

18.2 Progress under Weak Fairness

```
lemma wf_nodeOrder: "wf(nodeOrder j)"
apply (unfold nodeOrder_def)
apply (rule wf_measure [THEN wf_subset], blast)
done

lemma nodeOrder_eq:
     "[| i<N; j<N |] ==> ((next i, i) ∈ nodeOrder j) = (i ≠ j)"
  apply (cases ‹i < j›)
   apply (auto simp add: nodeOrder_def next_def mod_Suc add.commute [of _
N])
  apply (simp only: diff_add_assoc mod_add_self1)
  apply simp
  done
```

From "A Logic for Concurrent Programming", but not used in Chapter 4. Note the use of `cases`. Reasoning about leadsTo takes practice!

```
lemma TR7_nodeOrder:
     "[| i<N; j<N |] ==>
      F ∈ (HasTok i) leadsTo ({s. (token s, i) ∈ nodeOrder j} ∪ HasTok j)"
apply (cases "i=j")
apply (blast intro: subset_imp_leadsTo)
apply (rule TR7 [THEN leadsTo_weaken_R])
apply (auto simp add: HasTok_def nodeOrder_eq)
done
```

Chapter 4 variant, the one actually used below.

```
lemma TR7_aux: "[| i<N; j<N; i≠j |]
      ==> F ∈ (HasTok i) leadsTo {s. (token s, i) ∈ nodeOrder j}"
apply (rule TR7 [THEN leadsTo_weaken_R])
apply (auto simp add: HasTok_def nodeOrder_eq)
done

lemma token_lemma:
     "({s. token s < N} ∩ token -‘ {m}) = (if m<N then token -‘ {m} else {})"
by auto
```

Misra's TR9: the token reaches an arbitrary node

```
lemma leadsTo_j: "j<N ==> F ∈ {s. token s < N} leadsTo (HasTok j)"
apply (rule leadsTo_weaken_R)
apply (rule_tac I = "-{j}" and f = token and B = "{}"
       in wf_nodeOrder [THEN bounded_induct])
apply (simp_all (no_asm_simp) add: token_lemma vimage_Diff HasTok_def)
 prefer 2 apply blast
apply clarify
apply (rule TR7_aux [THEN leadsTo_weaken])
apply (auto simp add: HasTok_def nodeOrder_def)
done
```

Misra's TR8: a hungry process eventually eats

```
lemma token_progress:
     "j<N ==> F ∈ ({s. token s < N} ∩ H j) leadsTo (E j)"
apply (rule leadsTo_cancel1 [THEN leadsTo_Un_duplicate])
apply (rule_tac [2] TR6)
apply (rule psp [OF leadsTo_j TR3, THEN leadsTo_weaken], blast+)
done

end

end


theory Channel imports "../UNITY_Main" begin

type_synonym state = "nat set"

consts
  F :: "state program"

definition minSet :: "nat set => nat option" where
    "minSet A == if A={} then None else Some (LEAST x. x ∈ A)"

axiomatization where

  UC1:  "F ∈ (minSet -‘ {Some x}) co (minSet -‘ (Some‘atLeast x))" and



  UC2:  "F ∈ (minSet -‘ {Some x}) leadsTo {s. x ∉ s}"



lemma minSet_eq_SomeD: "minSet A = Some x ==> x ∈ A"
apply (unfold minSet_def)
apply (simp split: if_split_asm)
apply (fast intro: LeastI)
done

lemma minSet_empty [simp]: " minSet{} = None"
by (unfold minSet_def, simp)

lemma minSet_nonempty: "x ∈ A ==> minSet A = Some (LEAST x. x ∈ A)"
by (unfold minSet_def, auto)

lemma minSet_greaterThan:
     "F ∈ (minSet -‘ {Some x}) leadsTo (minSet -‘ (Some‘greaterThan x))"
apply (rule leadsTo_weaken)
apply (rule_tac x1=x in psp [OF UC2 UC1], safe)
apply (auto dest: minSet_eq_SomeD simp add: linorder_neq_iff)
done


lemma Channel_progress_lemma:
     "F ∈ (UNIV-{{}}) leadsTo (minSet -‘ (Some‘atLeast y))"
```

```
apply (rule leadsTo_weaken_R)
apply (rule_tac l = y and f = "the o minSet" and B = "{}"
       in greaterThan_bounded_induct, safe)
apply (simp_all (no_asm_simp))
apply (drule_tac [2] minSet_nonempty)
 prefer 2 apply simp
apply (rule minSet_greaterThan [THEN leadsTo_weaken], safe)
apply simp_all
apply (drule minSet_nonempty, simp)
done


lemma Channel_progress: "!!y::nat. F ∈ (UNIV-{{}}) leadsTo {s. y ∉ s}"
apply (rule Channel_progress_lemma [THEN leadsTo_weaken_R], clarify)
apply (frule minSet_nonempty)
apply (auto dest: Suc_le_lessD not_less_Least)
done

end


theory Lift
imports "../UNITY_Main"
begin

record state =
  floor :: "int"            — current position of the lift
  "open" :: "bool"          — whether the door is opened at floor
  stop  :: "bool"           — whether the lift is stopped at floor
  req   :: "int set"        — for each floor, whether the lift is requested
  up    :: "bool"           — current direction of movement
  move  :: "bool"           — whether moving takes precedence over opening

axiomatization
  Min :: "int" and    — least and greatest floors
  Max :: "int"        — least and greatest floors
where
  Min_le_Max [iff]: "Min ≤ Max"


  — Abbreviations: the "always" part

definition
  above :: "state set"
  where "above = {s. ∃i. floor s < i & i ≤ Max & i ∈ req s}"

definition
  below :: "state set"
  where "below = {s. ∃i. Min ≤ i & i < floor s & i ∈ req s}"

definition
  queueing :: "state set"
  where "queueing = above ∪ below"
```

definition
```
goingup :: "state set"
```
where `"goingup = above ∩ ({s. up s}  ∪ -below)"`

definition
```
goingdown :: "state set"
```
where `"goingdown = below ∩ ({s. ~ up s} ∪ -above)"`

definition
```
ready :: "state set"
```
where `"ready = {s. stop s & ~ open s & move s}"`

— Further abbreviations

definition
```
moving :: "state set"
```
where `"moving = {s. ~ stop s & ~ open s}"`

definition
```
stopped :: "state set"
```
where `"stopped = {s. stop s  & ~ open s & ~ move s}"`

definition
```
opened :: "state set"
```
where `"opened = {s. stop s  &  open s  &  move s}"`

definition
```
closed :: "state set"
```
— but this is the same as ready!!
where `"closed = {s. stop s  & ~ open s &  move s}"`

definition
```
atFloor :: "int => state set"
```
where `"atFloor n = {s. floor s = n}"`

definition
```
Req :: "int => state set"
```
where `"Req n = {s. n ∈ req s}"`

— The program

definition
```
request_act :: "(state*state) set"
```
where
```
"request_act = {(s,s'). s' = s (|stop:=True, move:=False|)
                              & ~ stop s & floor s ∈ req s}"
```

definition
```
open_act :: "(state*state) set"
```
where
```
"open_act =
       {(s,s'). s' = s (|open :=True,
                         req  := req s - {floor s},
                         move := True|)
                      & stop s & ~ open s & floor s ∈ req s
```

```
                    & ~(move s & s ∈ queueing)}"
```

definition
```
  close_act :: "(state*state) set"
```
where `"close_act = {(s,s'). s' = s (|open := False|) & open s}"`

definition
```
  req_up :: "(state*state) set"
```
where
```
"req_up =
       {(s,s'). s' = s (|stop  :=False,
                         floor := floor s + 1,
                         up    := True|)
                    & s ∈ (ready ∩ goingup)}"
```

definition
```
  req_down :: "(state*state) set"
```
where
```
"req_down =
       {(s,s'). s' = s (|stop  :=False,
                         floor := floor s - 1,
                         up    := False|)
                    & s ∈ (ready ∩ goingdown)}"
```

definition
```
  move_up :: "(state*state) set"
```
where
```
"move_up =
       {(s,s'). s' = s (|floor := floor s + 1|)
                    & ~ stop s & up s & floor s ∉ req s}"
```

definition
```
  move_down :: "(state*state) set"
```
where
```
"move_down =
       {(s,s'). s' = s (|floor := floor s - 1|)
                    & ~ stop s & ~ up s & floor s ∉ req s}"
```

definition
```
  button_press  :: "(state*state) set"
```
— This action is omitted from prior treatments, which therefore are unrealistic: nobody asks the lift to do anything! But adding this action invalidates many of the existing progress arguments: various "ensures" properties fail. Maybe it should be constrained to only allow button presses in the current direction of travel, like in a real lift.

where
```
"button_press =
       {(s,s'). ∃n. s' = s (|req := insert n (req s)|)
                     & Min ≤ n & n ≤ Max}"
```

definition
```
  Lift :: "state program"
```
— for the moment, we OMIT `button_press`

where
```
"Lift = mk_total_program
              ({s. floor s = Min & ~ up s & move s & stop s &
                        ~ open s & req s = {}},
               {request_act, open_act, close_act,
                req_up, req_down, move_up, move_down},
```

```
              UNIV)"
```

— Invariants

definition
```
  bounded :: "state set"
```
where *"bounded = {s. Min ≤ floor s & floor s ≤ Max}"*

definition
```
  open_stop :: "state set"
```
where *"open_stop = {s. open s --> stop s}"*

definition
```
  open_move :: "state set"
```
where *"open_move = {s. open s --> move s}"*

definition
```
  stop_floor :: "state set"
```
where *"stop_floor = {s. stop s & ~ move s --> floor s ∈ req s}"*

definition
```
  moving_up :: "state set"
```
where
```
"moving_up = {s. ~ stop s & up s -->
                (∃f. floor s ≤ f & f ≤ Max & f ∈ req s)}"
```

definition
```
  moving_down :: "state set"
```
where
```
"moving_down = {s. ~ stop s & ~ up s -->
                  (∃f. Min ≤ f & f ≤ floor s & f ∈ req s)}"
```

definition
```
  metric :: "[int,state] => int"
```
where
```
"metric =
     (%n s. if floor s < n then (if up s then n - floor s
                                 else (floor s - Min) + (n-Min))
            else
            if n < floor s then (if up s then (Max - floor s) + (Max-n)
                                 else floor s - n)
            else 0)"
```

locale *Floor =*
```
  fixes n
```
assumes
```
  Min_le_n [iff]: "Min ≤ n"
```
and
```
  n_le_Max [iff]: "n ≤ Max"
```

lemma
```
not_mem_distinct: "[| x ∉ A;  y ∈ A |] ==> x ≠ y"
```
by *blast*

declare *Lift_def [THEN def_prg_Init, simp]*

declare *request_act_def [THEN def_act_simp, simp]*
declare *open_act_def [THEN def_act_simp, simp]*

```
declare close_act_def [THEN def_act_simp, simp]
declare req_up_def [THEN def_act_simp, simp]
declare req_down_def [THEN def_act_simp, simp]
declare move_up_def [THEN def_act_simp, simp]
declare move_down_def [THEN def_act_simp, simp]
declare button_press_def [THEN def_act_simp, simp]


declare above_def [THEN def_set_simp, simp]
declare below_def [THEN def_set_simp, simp]
declare queueing_def [THEN def_set_simp, simp]
declare goingup_def [THEN def_set_simp, simp]
declare goingdown_def [THEN def_set_simp, simp]
declare ready_def [THEN def_set_simp, simp]


declare bounded_def [simp]
        open_stop_def [simp]
        open_move_def [simp]
        stop_floor_def [simp]
        moving_up_def [simp]
        moving_down_def [simp]

lemma open_stop: "Lift ∈ Always open_stop"
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety)
done

lemma stop_floor: "Lift ∈ Always stop_floor"
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety)
done


lemma open_move: "Lift ∈ Always open_move"
apply (cut_tac open_stop)
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety)
done

lemma moving_up: "Lift ∈ Always moving_up"
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety)
apply (auto dest: order_le_imp_less_or_eq simp add: add1_zle_eq)
done

lemma moving_down: "Lift ∈ Always moving_down"
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety)
apply (blast dest: order_le_imp_less_or_eq)
done

lemma bounded: "Lift ∈ Always bounded"
apply (cut_tac moving_up moving_down)
```

```
apply (rule AlwaysI, force)
apply (unfold Lift_def, safety, auto)
apply (drule not_mem_distinct, assumption, arith)+
done
```

18.3 Progress

```
declare moving_def [THEN def_set_simp, simp]
declare stopped_def [THEN def_set_simp, simp]
declare opened_def [THEN def_set_simp, simp]
declare closed_def [THEN def_set_simp, simp]
declare atFloor_def [THEN def_set_simp, simp]
declare Req_def [THEN def_set_simp, simp]
```

The HUG'93 paper mistakenly omits the Req n from these!

```
lemma E_thm01: "Lift ∈ (stopped ∩ atFloor n) LeadsTo (opened ∩ atFloor
n)"
apply (cut_tac stop_floor)
apply (unfold Lift_def, ensures_tac "open_act")
done
```

```
lemma E_thm02: "Lift ∈ (Req n ∩ stopped - atFloor n) LeadsTo
                       (Req n ∩ opened - atFloor n)"
apply (cut_tac stop_floor)
apply (unfold Lift_def, ensures_tac "open_act")
done

lemma E_thm03: "Lift ∈ (Req n ∩ opened - atFloor n) LeadsTo
                       (Req n ∩ closed - (atFloor n - queueing))"
apply (unfold Lift_def, ensures_tac "close_act")
done

lemma E_thm04: "Lift ∈ (Req n ∩ closed ∩ (atFloor n - queueing))
                       LeadsTo (opened ∩ atFloor n)"
apply (unfold Lift_def, ensures_tac "open_act")
done
```

```
lemmas linorder_leI = linorder_not_less [THEN iffD1]

context Floor
begin

lemmas le_MinD = Min_le_n [THEN order_antisym]
  and Max_leD = n_le_Max [THEN [2] order_antisym]

declare le_MinD [dest!]
  and linorder_leI [THEN le_MinD, dest!]
  and Max_leD [dest!]
```

```
  and linorder_leI [THEN Max_leD, dest!]


lemma E_thm05c:
    "Lift ∈ (Req n ∩ closed - (atFloor n - queueing))
            LeadsTo ((closed ∩ goingup ∩ Req n)  ∪
                     (closed ∩ goingdown ∩ Req n))"
by (auto intro!: subset_imp_LeadsTo simp add: linorder_neq_iff)


lemma lift_2: "Lift ∈ (Req n ∩ closed - (atFloor n - queueing))
            LeadsTo (moving ∩ Req n)"
apply (rule LeadsTo_Trans [OF E_thm05c LeadsTo_Un])
apply (unfold Lift_def)
apply (ensures_tac [2] "req_down")
apply (ensures_tac "req_up", auto)
done



declare if_split_asm [split]


lemma E_thm12a:
     "0 < N ==>
      Lift ∈ (moving ∩ Req n ∩ {s. metric n s = N} ∩
              {s. floor s ∉ req s} ∩ {s. up s})
             LeadsTo
               (moving ∩ Req n ∩ {s. metric n s < N})"
apply (cut_tac moving_up)
apply (unfold Lift_def, ensures_tac "move_up", safe)

apply (erule linorder_leI [THEN order_antisym, symmetric])
apply (auto simp add: metric_def)
done



lemma E_thm12b: "0 < N ==>
      Lift ∈ (moving ∩ Req n ∩ {s. metric n s = N} ∩
              {s. floor s ∉ req s} - {s. up s})
             LeadsTo (moving ∩ Req n ∩ {s. metric n s < N})"
apply (cut_tac moving_down)
apply (unfold Lift_def, ensures_tac "move_down", safe)

apply (erule linorder_leI [THEN order_antisym, symmetric])
apply (auto simp add: metric_def)
done


lemma lift_4:
```

```
     "0<N ==> Lift ∈ (moving ∩ Req n ∩ {s. metric n s = N} ∩
                           {s. floor s ∉ req s}) LeadsTo
                          (moving ∩ Req n ∩ {s. metric n s < N})"
apply (rule LeadsTo_Trans [OF subset_imp_LeadsTo
                              LeadsTo_Un [OF E_thm12a E_thm12b]], auto)
done
```

```
lemma E_thm16a: "0<N
  ==> Lift ∈ (closed ∩ Req n ∩ {s. metric n s = N} ∩ goingup) LeadsTo
             (moving ∩ Req n ∩ {s. metric n s < N})"
apply (cut_tac bounded)
apply (unfold Lift_def, ensures_tac "req_up")
apply (auto simp add: metric_def)
done
```

```
lemma E_thm16b: "0<N ==>
      Lift ∈ (closed ∩ Req n ∩ {s. metric n s = N} ∩ goingdown) LeadsTo
                  (moving ∩ Req n ∩ {s. metric n s < N})"
apply (cut_tac bounded)
apply (unfold Lift_def, ensures_tac "req_down")
apply (auto simp add: metric_def)
done
```

```
lemma E_thm16c:
     "0<N ==> Req n ∩ {s. metric n s = N} ⊆ goingup ∪ goingdown"
by (force simp add: metric_def)
```

```
lemma lift_5:
     "0<N ==> Lift ∈ (closed ∩ Req n ∩ {s. metric n s = N}) LeadsTo
                    (moving ∩ Req n ∩ {s. metric n s < N})"
apply (rule LeadsTo_Trans [OF subset_imp_LeadsTo
                              LeadsTo_Un [OF E_thm16a E_thm16b]])
apply (drule E_thm16c, auto)
done
```

```
lemma metric_eq_0D [dest]:
     "[| metric n s = 0;  Min ≤ floor s;  floor s ≤ Max |] ==> floor s =
n"
by (force simp add: metric_def)
```

```
lemma E_thm11: "Lift ∈ (moving ∩ Req n ∩ {s. metric n s = 0}) LeadsTo
                      (stopped ∩ atFloor n)"
apply (cut_tac bounded)
apply (unfold Lift_def, ensures_tac "request_act", auto)
done


lemma E_thm13:
  "Lift ∈ (moving ∩ Req n ∩ {s. metric n s = N} ∩ {s. floor s ∈ req s})

  LeadsTo (stopped ∩ Req n ∩ {s. metric n s = N} ∩ {s. floor s ∈ req s})"
apply (unfold Lift_def, ensures_tac "request_act")
apply (auto simp add: metric_def)
done


lemma E_thm14: "0 < N ==>
      Lift ∈
        (stopped ∩ Req n ∩ {s. metric n s = N} ∩ {s. floor s ∈ req s})
        LeadsTo (opened ∩ Req n ∩ {s. metric n s = N})"
apply (unfold Lift_def, ensures_tac "open_act")
apply (auto simp add: metric_def)
done


lemma E_thm15: "Lift ∈ (opened ∩ Req n ∩ {s. metric n s = N})
             LeadsTo (closed ∩ Req n ∩ {s. metric n s = N})"
apply (unfold Lift_def, ensures_tac "close_act")
apply (auto simp add: metric_def)
done




lemma lift_3_Req: "0 < N ==>
      Lift ∈
        (moving ∩ Req n ∩ {s. metric n s = N} ∩ {s. floor s ∈ req s})
        LeadsTo (moving ∩ Req n ∩ {s. metric n s < N})"
apply (blast intro!: E_thm13 E_thm14 E_thm15 lift_5 intro: LeadsTo_Trans)
done



lemma Always_nonneg: "Lift ∈ Always {s. 0 ≤ metric n s}"
apply (rule bounded [THEN Always_weaken])
apply (auto simp add: metric_def)
done

lemmas R_thm11 = Always_LeadsTo_weaken [OF Always_nonneg E_thm11]

lemma lift_3: "Lift ∈ (moving ∩ Req n) LeadsTo (stopped ∩ atFloor n)"
apply (rule Always_nonneg [THEN integ_0_le_induct])
```

```
apply (case_tac "0 < z")

prefer 2 apply (force intro: R_thm11 order_antisym simp add: linorder_not_less)
apply (rule LeadsTo_weaken_R [OF asm_rl Un_upper1])
apply (rule LeadsTo_Trans [OF subset_imp_LeadsTo
                              LeadsTo_Un [OF lift_4 lift_3_Req]], auto)
done


lemma lift_1: "Lift ∈ (Req n) LeadsTo (opened ∩ atFloor n)"
apply (rule LeadsTo_Trans)
 prefer 2
 apply (rule LeadsTo_Un [OF E_thm04 LeadsTo_Un_post])
 apply (rule E_thm01 [THEN [2] LeadsTo_Trans_Un])
 apply (rule lift_3 [THEN [2] LeadsTo_Trans_Un])
 apply (rule lift_2 [THEN [2] LeadsTo_Trans_Un])
 apply (rule LeadsTo_Trans_Un [OF E_thm02 E_thm03])
apply (rule open_move [THEN Always_LeadsToI])
apply (rule Always_LeadsToI [OF open_stop subset_imp_LeadsTo], clarify)

apply (case_tac "open x", auto)
done

end

end


theory Mutex imports "../UNITY_Main" begin

record state =
  p :: bool
  m :: int
  n :: int
  u :: bool
  v :: bool

type_synonym command = "(state*state) set"




definition U0 :: command
  where "U0 = {(s,s'). s' = s (|u:=True, m:=1|) & m s = 0}"

definition  U1 :: command
  where "U1 = {(s,s'). s' = s (|p:= v s, m:=2|) & m s = 1}"

definition  U2 :: command
  where "U2 = {(s,s'). s' = s (|m:=3|) & ~ p s & m s = 2}"

definition  U3 :: command
  where "U3 = {(s,s'). s' = s (|u:=False, m:=4|) & m s = 3}"
```

```
definition U4 :: command
  where "U4 = {(s,s'). s' = s (|p:=True, m:=0|) & m s = 4}"



definition V0 :: command
  where "V0 = {(s,s'). s' = s (|v:=True, n:=1|) & n s = 0}"

definition V1 :: command
  where "V1 = {(s,s'). s' = s (|p:= ~ u s, n:=2|) & n s = 1}"

definition V2 :: command
  where "V2 = {(s,s'). s' = s (|n:=3|) & p s & n s = 2}"

definition V3 :: command
  where "V3 = {(s,s'). s' = s (|v:=False, n:=4|) & n s = 3}"

definition V4 :: command
  where "V4 = {(s,s'). s' = s (|p:=False, n:=0|) & n s = 4}"

definition Mutex :: "state program"
  where "Mutex = mk_total_program
                ({s. ~ u s & ~ v s & m s = 0 & n s = 0},
                 {U0, U1, U2, U3, U4, V0, V1, V2, V3, V4},
                 UNIV)"



definition IU :: "state set"
  where "IU = {s. (u s = (1 ≤ m s & m s ≤ 3)) & (m s = 3 --> ~ p s)}"

definition IV :: "state set"
  where "IV = {s. (v s = (1 ≤ n s & n s ≤ 3)) & (n s = 3 --> p s)}"



definition bad_IU :: "state set"
  where "bad_IU = {s. (u s = (1 ≤ m s & m s ≤ 3)) &
                  (3 ≤ m s & m s ≤ 4 --> ~ p s)}"


declare Mutex_def [THEN def_prg_Init, simp]

declare U0_def [THEN def_act_simp, simp]
declare U1_def [THEN def_act_simp, simp]
declare U2_def [THEN def_act_simp, simp]
declare U3_def [THEN def_act_simp, simp]
declare U4_def [THEN def_act_simp, simp]
declare V0_def [THEN def_act_simp, simp]
declare V1_def [THEN def_act_simp, simp]
declare V2_def [THEN def_act_simp, simp]
declare V3_def [THEN def_act_simp, simp]
declare V4_def [THEN def_act_simp, simp]
```

```
declare IU_def [THEN def_set_simp, simp]
declare IV_def [THEN def_set_simp, simp]
declare bad_IU_def [THEN def_set_simp, simp]

lemma IU: "Mutex ∈ Always IU"
apply (rule AlwaysI, force)
apply (unfold Mutex_def, safety)
done


lemma IV: "Mutex ∈ Always IV"
apply (rule AlwaysI, force)
apply (unfold Mutex_def, safety)
done


lemma mutual_exclusion: "Mutex ∈ Always {s. ~ (m s = 3 & n s = 3)}"
apply (rule Always_weaken)
apply (rule Always_Int_I [OF IU IV], auto)
done



lemma "Mutex ∈ Always bad_IU"
apply (rule AlwaysI, force)
apply (unfold Mutex_def, safety, auto)

oops


lemma eq_123: "((1::int) ≤ i & i ≤ 3) = (i = 1 | i = 2 | i = 3)"
by arith



lemma U_F0: "Mutex ∈ {s. m s=2} Unless {s. m s=3}"
by (unfold Unless_def Mutex_def, safety)

lemma U_F1: "Mutex ∈ {s. m s=1} LeadsTo {s. p s = v s & m s = 2}"
by (unfold Mutex_def, ensures_tac U1)

lemma U_F2: "Mutex ∈ {s. ~ p s & m s = 2} LeadsTo {s. m s = 3}"
apply (cut_tac IU)
apply (unfold Mutex_def, ensures_tac U2)
done

lemma U_F3: "Mutex ∈ {s. m s = 3} LeadsTo {s. p s}"
apply (rule_tac B = "{s. m s = 4}" in LeadsTo_Trans)
 apply (unfold Mutex_def)
 apply (ensures_tac U3)
apply (ensures_tac U4)
done
```

```
lemma U_lemma2: "Mutex ∈ {s. m s = 2} LeadsTo {s. p s}"
apply (rule LeadsTo_Diff [OF LeadsTo_weaken_L
                             Int_lower2 [THEN subset_imp_LeadsTo]])
apply (rule LeadsTo_Trans [OF U_F2 U_F3], auto)
done

lemma U_lemma1: "Mutex ∈ {s. m s = 1} LeadsTo {s. p s}"
by (rule LeadsTo_Trans [OF U_F1 [THEN LeadsTo_weaken_R] U_lemma2], blast)

lemma U_lemma123: "Mutex ∈ {s. 1 ≤ m s & m s ≤ 3} LeadsTo {s. p s}"
by (simp add: eq_123 Collect_disj_eq LeadsTo_Un_distrib U_lemma1 U_lemma2
U_F3)


lemma u_Leadsto_p: "Mutex ∈ {s. u s} LeadsTo {s. p s}"
by (rule Always_LeadsTo_weaken [OF IU U_lemma123], auto)




lemma V_F0: "Mutex ∈ {s. n s=2} Unless {s. n s=3}"
by (unfold Unless_def Mutex_def, safety)

lemma V_F1: "Mutex ∈ {s. n s=1} LeadsTo {s. p s = (~ u s) & n s = 2}"
by (unfold Mutex_def, ensures_tac "V1")

lemma V_F2: "Mutex ∈ {s. p s & n s = 2} LeadsTo {s. n s = 3}"
apply (cut_tac IV)
apply (unfold Mutex_def, ensures_tac "V2")
done

lemma V_F3: "Mutex ∈ {s. n s = 3} LeadsTo {s. ~ p s}"
apply (rule_tac B = "{s. n s = 4}" in LeadsTo_Trans)
 apply (unfold Mutex_def)
 apply (ensures_tac V3)
apply (ensures_tac V4)
done

lemma V_lemma2: "Mutex ∈ {s. n s = 2} LeadsTo {s. ~ p s}"
apply (rule LeadsTo_Diff [OF LeadsTo_weaken_L
                             Int_lower2 [THEN subset_imp_LeadsTo]])
apply (rule LeadsTo_Trans [OF V_F2 V_F3], auto)
done

lemma V_lemma1: "Mutex ∈ {s. n s = 1} LeadsTo {s. ~ p s}"
by (rule LeadsTo_Trans [OF V_F1 [THEN LeadsTo_weaken_R] V_lemma2], blast)

lemma V_lemma123: "Mutex ∈ {s. 1 ≤ n s & n s ≤ 3} LeadsTo {s. ~ p s}"
by (simp add: eq_123 Collect_disj_eq LeadsTo_Un_distrib V_lemma1 V_lemma2
V_F3)
```

```
lemma v_Leadsto_not_p: "Mutex ∈ {s. v s} LeadsTo {s. ~ p s}"
by (rule Always_LeadsTo_weaken [OF IV V_lemma123], auto)
```

```
lemma m1_Leadsto_3: "Mutex ∈ {s. m s = 1} LeadsTo {s. m s = 3}"
apply (rule LeadsTo_cancel2 [THEN LeadsTo_Un_duplicate])
apply (rule_tac [2] U_F2)
apply (simp add: Collect_conj_eq)
apply (subst Un_commute)
apply (rule LeadsTo_cancel2 [THEN LeadsTo_Un_duplicate])
 apply (rule_tac [2] PSP_Unless [OF v_Leadsto_not_p U_F0])
apply (rule U_F1 [THEN LeadsTo_weaken_R], auto)
done
```

```
lemma n1_Leadsto_3: "Mutex ∈ {s. n s = 1} LeadsTo {s. n s = 3}"
apply (rule LeadsTo_cancel2 [THEN LeadsTo_Un_duplicate])
apply (rule_tac [2] V_F2)
apply (simp add: Collect_conj_eq)
apply (subst Un_commute)
apply (rule LeadsTo_cancel2 [THEN LeadsTo_Un_duplicate])
 apply (rule_tac [2] PSP_Unless [OF u_Leadsto_p V_F0])
apply (rule V_F1 [THEN LeadsTo_weaken_R], auto)
done

end
```

```
theory Reach imports "../UNITY_Main" begin

typedecl vertex

type_synonym state = "vertex=>bool"

consts
  init ::  "vertex"

  edges :: "(vertex*vertex) set"

definition asgt :: "[vertex,vertex] => (state*state) set"
  where "asgt u v = {(s,s'). s' = s(v:= s u | s v)}"

definition Rprg :: "state program"
  where "Rprg = mk_total_program ({%v. v=init}, ⋃(u,v)∈edges. {asgt u v},
UNIV)"

definition reach_invariant :: "state set"
  where "reach_invariant = {s. (∀v. s v --> (init, v) ∈ edges*) & s init}"

definition fixedpoint :: "state set"
```

```
  where "fixedpoint = {s. ∀(u,v)∈edges. s u --> s v}"

definition metric :: "state => nat"
  where "metric s = card {v. ~ s v}"
```

*We assume that the set of vertices is finite

```
axiomatization where
  finite_graph:  "finite (UNIV :: vertex set)"



lemma ifE [elim!]:
    "[| if P then Q else R;
        [| P;   Q |] ==> S;
        [| ~ P; R |] ==> S |] ==> S"
by (simp split: if_split_asm)


declare Rprg_def [THEN def_prg_Init, simp]

declare asgt_def [THEN def_act_simp,simp]
```

All vertex sets are finite

```
declare finite_subset [OF subset_UNIV finite_graph, iff]

declare reach_invariant_def [THEN def_set_simp, simp]

lemma reach_invariant: "Rprg ∈ Always reach_invariant"
apply (rule AlwaysI, force)
apply (unfold Rprg_def, safety)
apply (blast intro: rtrancl_trans)
done



lemma fixedpoint_invariant_correct:
     "fixedpoint ∩ reach_invariant = { %v. (init, v) ∈ edges* }"
apply (unfold fixedpoint_def)
apply (rule equalityI)
apply (auto intro!: ext)
apply (erule rtrancl_induct, auto)
done

lemma lemma1:
     "FP Rprg ⊆ fixedpoint"
apply (simp add: FP_def fixedpoint_def Rprg_def mk_total_program_def)
apply (auto simp add: stable_def constrains_def)
apply (drule bspec, assumption)
apply (simp add: Image_singleton image_iff)
apply (drule fun_cong, auto)
```

```
done

lemma lemma2:
     "fixedpoint ⊆ FP Rprg"
apply (simp add: FP_def fixedpoint_def Rprg_def mk_total_program_def)
apply (auto intro!: ext simp add: stable_def constrains_def)
done

lemma FP_fixedpoint: "FP Rprg = fixedpoint"
by (rule equalityI [OF lemma1 lemma2])



lemma Compl_fixedpoint: "- fixedpoint = (⋃(u,v)∈edges. {s. s u & ~ s v})"
apply (simp add: FP_fixedpoint [symmetric] Rprg_def mk_total_program_def)
apply (rule subset_antisym)
apply (auto simp add: Compl_FP UN_UN_flatten)
 apply (rule fun_upd_idem, force)
apply (force intro!: rev_bexI simp add: fun_upd_idem_iff)
done

lemma Diff_fixedpoint:
     "A - fixedpoint = (⋃(u,v)∈edges. A ∩ {s. s u & ~ s v})"
by (simp add: Diff_eq Compl_fixedpoint, blast)



lemma Suc_metric: "~ s x ==> Suc (metric (s(x:=True))) = metric s"
apply (unfold metric_def)
apply (subgoal_tac "{v. ~ (s (x:=True)) v} = {v. ~ s v} - {x}")
 prefer 2 apply force
apply (simp add: card_Suc_Diff1 del:card_Diff_insert)
done

lemma metric_less [intro!]: "~ s x ==> metric (s(x:=True)) < metric s"
by (erule Suc_metric [THEN subst], blast)

lemma metric_le: "metric (s(y:=s x | s y)) ≤ metric s"
  by (cases "s x --> s y") (auto intro: less_imp_le simp add: fun_upd_idem)

lemma LeadsTo_Diff_fixedpoint:
     "Rprg ∈ ((metric-‘{m}) - fixedpoint) LeadsTo (metric-‘(lessThan m))"
apply (simp (no_asm) add: Diff_fixedpoint Rprg_def)
apply (rule LeadsTo_UN, auto)
apply (ensures_tac "asgt a b")
 prefer 2 apply blast
apply (simp (no_asm_use) add: linorder_not_less)
apply (drule metric_le [THEN order_antisym])
apply (auto elim: less_not_refl3 [THEN [2] rev_notE])
done

lemma LeadsTo_Un_fixedpoint:
```

```
    "Rprg ∈ (metric-‘{m}) LeadsTo (metric-‘(lessThan m) ∪ fixedpoint)"
apply (rule LeadsTo_Diff [OF LeadsTo_Diff_fixedpoint [THEN LeadsTo_weaken_R]
                             subset_imp_LeadsTo], auto)
done


lemma LeadsTo_fixedpoint: "Rprg ∈ UNIV LeadsTo fixedpoint"
apply (rule LessThan_induct, auto)
apply (rule LeadsTo_Un_fixedpoint)
done

lemma LeadsTo_correct: "Rprg ∈ UNIV LeadsTo { %v. (init, v) ∈ edges* }"
apply (subst fixedpoint_invariant_correct [symmetric])
apply (rule Always_LeadsTo_weaken [OF reach_invariant LeadsTo_fixedpoint],
auto)
done

end


theory Reachability imports "../Detects" Reach begin

type_synonym edge = "vertex * vertex"

record state =
  reach :: "vertex => bool"
  nmsg  :: "edge => nat"

consts root :: "vertex"
       E :: "edge set"
       V :: "vertex set"

inductive_set REACHABLE :: "edge set"
  where
    base: "v ∈ V ==> ((v,v) ∈ REACHABLE)"
  | step: "((u,v) ∈ REACHABLE) & (v,w) ∈ E ==> ((u,w) ∈ REACHABLE)"

definition reachable :: "vertex => state set" where
  "reachable p == {s. reach s p}"

definition nmsg_eq :: "nat => edge  => state set" where
  "nmsg_eq k == %e. {s. nmsg s e = k}"

definition nmsg_gt :: "nat => edge  => state set" where
  "nmsg_gt k  == %e. {s. k < nmsg s e}"

definition nmsg_gte :: "nat => edge => state set" where
  "nmsg_gte k == %e. {s. k ≤ nmsg s e}"

definition nmsg_lte  :: "nat => edge => state set" where
  "nmsg_lte k  == %e. {s. nmsg s e ≤ k}"

definition final :: "state set" where
```

```
  "final == (⋂v∈V. reachable v <==> {s. (root, v) ∈ REACHABLE}) ∩
            (⋂((nmsg_eq 0) ‘ E))"

axiomatization
where
    Graph1: "root ∈ V" and

    Graph2: "(v,w) ∈ E ==> (v ∈ V) & (w ∈ V)" and

    MA1:  "F ∈ Always (reachable root)" and

    MA2:  "v ∈ V ==> F ∈ Always (- reachable v ∪ {s. ((root,v) ∈ REACHABLE)})"
and

    MA3:  "[|v ∈ V;w ∈ V|] ==> F ∈ Always (-(nmsg_gt 0 (v,w)) ∪ (reachable
v))" and

    MA4:  "(v,w) ∈ E ==>
           F ∈ Always (-(reachable v) ∪ (nmsg_gt 0 (v,w)) ∪ (reachable w))"
and

    MA5:  "[|v ∈ V; w ∈ V|]
           ==> F ∈ Always (nmsg_gte 0 (v,w) ∩ nmsg_lte (Suc 0) (v,w))" and

    MA6:  "[|v ∈ V|] ==> F ∈ Stable (reachable v)" and

    MA6b: "[|v ∈ V;w ∈ W|] ==> F ∈ Stable (reachable v ∩ nmsg_lte k (v,w))"
and

    MA7:  "[|v ∈ V;w ∈ V|] ==> F ∈ UNIV LeadsTo nmsg_eq 0 (v,w)"


lemmas E_imp_in_V_L = Graph2 [THEN conjunct1]
lemmas E_imp_in_V_R = Graph2 [THEN conjunct2]

lemma lemma2:
     "(v,w) ∈ E ==> F ∈ reachable v LeadsTo nmsg_eq 0 (v,w) ∩ reachable v"
apply (rule MA7 [THEN PSP_Stable, THEN LeadsTo_weaken_L])
apply (rule_tac [3] MA6)
apply (auto simp add: E_imp_in_V_L E_imp_in_V_R)
done

lemma Induction_base: "(v,w) ∈ E ==> F ∈ reachable v LeadsTo reachable w"
apply (rule MA4 [THEN Always_LeadsTo_weaken])
apply (rule_tac [2] lemma2)
apply (auto simp add: nmsg_eq_def nmsg_gt_def)
done

lemma REACHABLE_LeadsTo_reachable:
     "(v,w) ∈ REACHABLE ==> F ∈ reachable v LeadsTo reachable w"
apply (erule REACHABLE.induct)
apply (rule subset_imp_LeadsTo, blast)
apply (blast intro: LeadsTo_Trans Induction_base)
done
```

lemma *Detects_part1: "F ∈ {s. (root,v) ∈ REACHABLE} LeadsTo reachable v"*
apply *(rule single_LeadsTo_I)*
apply *(simp split: if_split_asm)*
apply *(rule MA1 [THEN Always_LeadsToI])*
apply *(erule REACHABLE_LeadsTo_reachable [THEN LeadsTo_weaken_L], auto)*
done

lemma *Reachability_Detected:*
"v ∈ V ==> F ∈ (reachable v) Detects {s. (root,v) ∈ REACHABLE}"
apply *(unfold Detects_def, auto)*
prefer *2* **apply** *(blast intro: MA2 [THEN Always_weaken])*
apply *(rule Detects_part1 [THEN LeadsTo_weaken_L], blast)*
done

lemma *LeadsTo_Reachability:*
"v ∈ V ==> F ∈ UNIV LeadsTo (reachable v <==> {s. (root,v) ∈ REACHABLE})"
by *(erule Reachability_Detected [THEN Detects_Imp_LeadstoEQ])*

lemma *Eq_lemma1:*
"(reachable v <==> {s. (root,v) ∈ REACHABLE}) =
{s. ((s ∈ reachable v) = ((root,v) ∈ REACHABLE))}"
by *(unfold Equality_def, blast)*

lemma *Eq_lemma2:*
"(reachable v <==> (if (root,v) ∈ REACHABLE then UNIV else {})) =
{s. ((s ∈ reachable v) = ((root,v) ∈ REACHABLE))}"
by *(unfold Equality_def, auto)*

lemma *final_lemma1:*
"(⋂v ∈ V. ⋂w ∈ V. {s. ((s ∈ reachable v) = ((root,v) ∈ REACHABLE))
&
s ∈ nmsg_eq 0 (v,w)})
⊆ final"
apply *(unfold final_def Equality_def, auto)*
apply *(frule E_imp_in_V_R)*
apply *(frule E_imp_in_V_L, blast)*
done

lemma *final_lemma2:*
"E≠{}

```
  ==> (⋂v ∈ V. ⋂e ∈ E. {s. ((s ∈ reachable v) = ((root,v) ∈ REACHABLE))}

                          ∩ nmsg_eq 0 e)    ⊆  final"
apply (unfold final_def Equality_def)
apply (auto split!: if_split)
apply (frule E_imp_in_V_L, blast)
done

lemma final_lemma3:
     "E≠{}
      ==> (⋂v ∈ V. ⋂e ∈ E.
           (reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩ nmsg_eq 0 e)
          ⊆ final"
apply (frule final_lemma2)
apply (simp (no_asm_use) add: Eq_lemma2)
done


lemma final_lemma4:
     "E≠{}
      ==> (⋂v ∈ V. ⋂e ∈ E.
           {s. ((s ∈ reachable v) = ((root,v) ∈ REACHABLE))} ∩ nmsg_eq 0
e)
          = final"
apply (rule subset_antisym)
apply (erule final_lemma2)
apply (unfold final_def Equality_def, blast)
done

lemma final_lemma5:
     "E≠{}
      ==> (⋂v ∈ V. ⋂e ∈ E.
           ((reachable v) <==> {s. (root,v) ∈ REACHABLE}) ∩ nmsg_eq 0 e)
          = final"
apply (frule final_lemma4)
apply (simp (no_asm_use) add: Eq_lemma2)
done


lemma final_lemma6:
     "(⋂v ∈ V. ⋂w ∈ V.
       (reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩ nmsg_eq 0 (v,w))
      ⊆ final"
apply (simp (no_asm) add: Eq_lemma2 Int_def)
apply (rule final_lemma1)
done


lemma final_lemma7:
     "final =
      (⋂v ∈ V. ⋂w ∈ V.
       ((reachable v) <==> {s. (root,v) ∈ REACHABLE}) ∩
       (-{s. (v,w) ∈ E} ∪ (nmsg_eq 0 (v,w))))"
apply (unfold final_def)
```

```
apply (rule subset_antisym, blast)
apply (auto split: if_split_asm)
apply (blast dest: E_imp_in_V_L E_imp_in_V_R)+
done
```

```
lemma not_REACHABLE_imp_Stable_not_reachable:
     "[| v ∈ V; (root,v) ∉ REACHABLE |] ==> F ∈ Stable (- reachable v)"
apply (drule MA2 [THEN AlwaysD], auto)
done

lemma Stable_reachable_EQ_R:
     "v ∈ V ==> F ∈ Stable (reachable v <==> {s. (root,v) ∈ REACHABLE})"
apply (simp (no_asm) add: Equality_def Eq_lemma2)
apply (blast intro: MA6 not_REACHABLE_imp_Stable_not_reachable)
done


lemma lemma4:
     "((nmsg_gte 0 (v,w) ∩ nmsg_lte (Suc 0) (v,w)) ∩
       (- nmsg_gt 0 (v,w) ∪ A))
      ⊆ A ∪ nmsg_eq 0 (v,w)"
apply (unfold nmsg_gte_def nmsg_lte_def nmsg_gt_def nmsg_eq_def, auto)
done


lemma lemma5:
     "reachable v ∩ nmsg_eq 0 (v,w) =
      ((nmsg_gte 0 (v,w) ∩ nmsg_lte (Suc 0) (v,w)) ∩
       (reachable v ∩ nmsg_lte 0 (v,w)))"
by (unfold nmsg_gte_def nmsg_lte_def nmsg_gt_def nmsg_eq_def, auto)

lemma lemma6:
     "- nmsg_gt 0 (v,w) ∪ reachable v ⊆ nmsg_eq 0 (v,w) ∪ reachable v"
apply (unfold nmsg_gte_def nmsg_lte_def nmsg_gt_def nmsg_eq_def, auto)
done

lemma Always_reachable_OR_nmsg_0:
     "[|v ∈ V; w ∈ V|] ==> F ∈ Always (reachable v ∪ nmsg_eq 0 (v,w))"
apply (rule Always_Int_I [OF MA5 MA3, THEN Always_weaken])
apply (rule_tac [5] lemma4, auto)
done

lemma Stable_reachable_AND_nmsg_0:
     "[|v ∈ V; w ∈ V|] ==> F ∈ Stable (reachable v ∩ nmsg_eq 0 (v,w))"
apply (subst lemma5)
apply (blast intro: MA5 Always_imp_Stable [THEN Stable_Int] MA6b)
done
```

```
lemma Stable_nmsg_0_OR_reachable:
     "[|v ∈ V; w ∈ V|] ==> F ∈ Stable (nmsg_eq 0 (v,w) ∪ reachable v)"
by (blast intro!: Always_weaken [THEN Always_imp_Stable] lemma6 MA3)

lemma not_REACHABLE_imp_Stable_not_reachable_AND_nmsg_0:
     "[| v ∈ V; w ∈ V; (root,v) ∉ REACHABLE |]
      ==> F ∈ Stable (- reachable v ∩ nmsg_eq 0 (v,w))"
apply (rule Stable_Int [OF MA2 [THEN Always_imp_Stable]
                           Stable_nmsg_0_OR_reachable,
            THEN Stable_eq])
   prefer 4 apply blast
apply auto
done

lemma Stable_reachable_EQ_R_AND_nmsg_0:
     "[| v ∈ V; w ∈ V |]
      ==> F ∈ Stable ((reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩
                      nmsg_eq 0 (v,w))"
by (simp add: Equality_def Eq_lemma2  Stable_reachable_AND_nmsg_0
              not_REACHABLE_imp_Stable_not_reachable_AND_nmsg_0)



lemma UNIV_lemma: "UNIV ⊆ (⋂v ∈ V. UNIV)"
by blast

lemmas UNIV_LeadsTo_completion =
    LeadsTo_weaken_L [OF Finite_stable_completion UNIV_lemma]

lemma LeadsTo_final_E_empty: "E={} ==> F ∈ UNIV LeadsTo final"
apply (unfold final_def, simp)
apply (rule UNIV_LeadsTo_completion)
  apply safe
 apply (erule LeadsTo_Reachability [simplified])
apply (drule Stable_reachable_EQ_R, simp)
done


lemma Leadsto_reachability_AND_nmsg_0:
     "[| v ∈ V; w ∈ V |]
      ==> F ∈ UNIV LeadsTo
             ((reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩ nmsg_eq 0 (v,w))"
apply (rule LeadsTo_Reachability [THEN LeadsTo_Trans], blast)
apply (subgoal_tac
         "F ∈ (reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩
              UNIV LeadsTo (reachable v <==> {s. (root,v) ∈ REACHABLE}) ∩

              nmsg_eq 0 (v,w) ")
apply simp
```

```
apply (rule PSP_Stable2)
apply (rule MA7)
apply (rule_tac [3] Stable_reachable_EQ_R, auto)
done

lemma LeadsTo_final_E_NOT_empty: "E≠{} ==> F ∈ UNIV LeadsTo final"
apply (rule LeadsTo_weaken_L [OF LeadsTo_weaken_R UNIV_lemma])
apply (rule_tac [2] final_lemma6)
apply (rule Finite_stable_completion)
  apply blast
 apply (rule UNIV_LeadsTo_completion)
   apply (blast intro: Stable_INT Stable_reachable_EQ_R_AND_nmsg_0
                   Leadsto_reachability_AND_nmsg_0)+
done

lemma LeadsTo_final: "F ∈ UNIV LeadsTo final"
apply (cases "E={}")
 apply (rule_tac [2] LeadsTo_final_E_NOT_empty)
apply (rule LeadsTo_final_E_empty, auto)
done




lemma Stable_final_E_empty: "E={} ==> F ∈ Stable final"
apply (unfold final_def, simp)
apply (rule Stable_INT)
apply (drule Stable_reachable_EQ_R, simp)
done


lemma Stable_final_E_NOT_empty: "E≠{} ==> F ∈ Stable final"
apply (subst final_lemma7)
apply (rule Stable_INT)
apply (rule Stable_INT)
apply (simp (no_asm) add: Eq_lemma2)
apply safe
apply (rule Stable_eq)
apply (subgoal_tac [2]
     "({s. (s ∈ reachable v) = ((root,v) ∈ REACHABLE) } ∩ nmsg_eq 0 (v,w))
=
      ({s. (s ∈ reachable v) = ( (root,v) ∈ REACHABLE) } ∩ (- UNIV ∪ nmsg_eq
0 (v,w)))")
prefer 2 apply blast
prefer 2 apply blast
apply (rule Stable_reachable_EQ_R_AND_nmsg_0
            [simplified Eq_lemma2 Collect_const])
apply (blast, blast)
apply (rule Stable_eq)
 apply (rule Stable_reachable_EQ_R [simplified Eq_lemma2 Collect_const])
 apply simp
apply (subgoal_tac
        "({s. (s ∈ reachable v) = ((root,v) ∈ REACHABLE) }) =
```

```
        ({s. (s ∈ reachable v) = ( (root,v) ∈ REACHABLE) } ∩
             (- {} ∪ nmsg_eq 0 (v,w)))")
apply blast+
done

lemma Stable_final: "F ∈ Stable final"
apply (cases "E={}")
 prefer 2 apply (blast intro: Stable_final_E_NOT_empty)
apply (blast intro: Stable_final_E_empty)
done

end
```

19 Analyzing the Needham-Schroeder Public-Key Protocol in UNITY

```
theory NSP_Bad imports "HOL-Auth.Public" "../UNITY_Main" begin
```

This is the flawed version, vulnerable to Lowe's attack. From page 260 of Burrows, Abadi and Needham. A Logic of Authentication. Proc. Royal Soc. 426 (1989).

```
type_synonym state = "event list"


definition
  Fake :: "(state*state) set"
  where "Fake = {(s,s'). 
              ∃B X. s' = Says Spy B X # s
                    & X ∈ synth (analz (spies s))}"




definition
  NS1 :: "(state*state) set"
  where "NS1 = {(s1,s'). 
            ∃A1 B NA.
                s' = Says A1 B (Crypt (pubK B) {|Nonce NA, Agent A1|}) # s1
             & Nonce NA ∉ used s1}"


definition
  NS2 :: "(state*state) set"
  where "NS2 = {(s2,s'). 
            ∃A' A2 B NA NB.
                s' = Says B A2 (Crypt (pubK A2) {|Nonce NA, Nonce NB|}) # s2
             & Says A' B (Crypt (pubK B) {|Nonce NA, Agent A2|}) ∈ set s2
             & Nonce NB ∉ used s2}"


definition
  NS3 :: "(state*state) set"
```

```
  where "NS3 = {(s3,s'). 
            ∃A3 B' B NA NB.
                s' = Says A3 B (Crypt (pubK B) (Nonce NB)) # s3
              & Says A3  B (Crypt (pubK B) {|Nonce NA, Agent A3|}) ∈ set s3
              & Says B' A3 (Crypt (pubK A3) {|Nonce NA, Nonce NB|}) ∈ set s3}"


definition Nprg :: "state program" where

    "Nprg = mk_total_program({[]}, {Fake, NS1, NS2, NS3}, UNIV)"

declare spies_partsEs [elim]
declare analz_into_parts [dest]
declare Fake_parts_insert_in_Un  [dest]
```

For other theories, e.g. Mutex and Lift, using [iff] slows proofs down. Here, it facilitates re-use of the Auth proofs.

```
declare Fake_def [THEN def_act_simp, iff]
declare NS1_def [THEN def_act_simp, iff]
declare NS2_def [THEN def_act_simp, iff]
declare NS3_def [THEN def_act_simp, iff]

declare Nprg_def [THEN def_prg_Init, simp]
```

A "possibility property": there are traces that reach the end. Replace by LEADSTO proof!

```
lemma "A ≠ B ==>
       ∃NB. ∃s ∈ reachable Nprg. Says A B (Crypt (pubK B) (Nonce NB)) ∈ set
s"
apply (intro exI bexI)
apply (rule_tac [2] act = "totalize_act NS3" in reachable.Acts)
apply (rule_tac [3] act = "totalize_act NS2" in reachable.Acts)
apply (rule_tac [4] act = "totalize_act NS1" in reachable.Acts)
apply (rule_tac [5] reachable.Init)
apply (simp_all (no_asm_simp) add: Nprg_def totalize_act_def)
apply auto
done
```

19.1 Inductive Proofs about *ns_public*

```
lemma ns_constrainsI:
     "(!!act s s'. [| act ∈ {Id, Fake, NS1, NS2, NS3};
                      (s,s') ∈ act;  s ∈ A |] ==> s' ∈ A')
      ==> Nprg ∈ A co A'"
apply (simp add: Nprg_def mk_total_program_def)
apply (rule constrainsI, auto)
done
```

This ML code does the inductions directly.

```
ML‹
fun ns_constrains_tac ctxt i =
  SELECT_GOAL
    (EVERY
```

```
     [REPEAT (eresolve_tac ctxt @{thms Always_ConstrainsI} 1),
      REPEAT (resolve_tac ctxt [@{thm StableI}, @{thm stableI}, @{thm constrains_imp_Constrains
1),
      resolve_tac ctxt @{thms ns_constrainsI} 1,
      full_simp_tac ctxt 1,
      REPEAT (FIRSTGOAL (eresolve_tac ctxt [disjE])),
      ALLGOALS (clarify_tac (ctxt delrules [impI, @{thm impCE}])),
      REPEAT (FIRSTGOAL (analz_mono_contra_tac ctxt)),
      ALLGOALS (asm_simp_tac ctxt)]) i;

(*Tactic for proving secrecy theorems*)
fun ns_induct_tac ctxt =
  (SELECT_GOAL o EVERY)
     [resolve_tac ctxt @{thms AlwaysI} 1,
      force_tac ctxt 1,
      (*"reachable" gets in here*)
      resolve_tac ctxt [@{thm Always_reachable} RS @{thm Always_ConstrainsI}
RS @{thm StableI}] 1,
      ns_constrains_tac ctxt 1];
›

method_setup ns_induct = ‹
    Scan.succeed (SIMPLE_METHOD' o ns_induct_tac)›
    "for inductive reasoning about the Needham-Schroeder protocol"
```

Converts invariants into statements about reachable states

```
lemmas Always_Collect_reachableD =
     Always_includes_reachable [THEN subsetD, THEN CollectD]
```

Spy never sees another agent's private key! (unless it's bad at start)

```
lemma Spy_see_priK:
     "Nprg ∈ Always {s. (Key (priK A) ∈ parts (spies s)) = (A ∈ bad)}"
apply ns_induct
apply blast
done
declare Spy_see_priK [THEN Always_Collect_reachableD, simp]

lemma Spy_analz_priK:
     "Nprg ∈ Always {s. (Key (priK A) ∈ analz (spies s)) = (A ∈ bad)}"
by (rule Always_reachable [THEN Always_weaken], auto)
declare Spy_analz_priK [THEN Always_Collect_reachableD, simp]
```

19.2 Authenticity properties obtained from NS2

It is impossible to re-use a nonce in both NS1 and NS2 provided the nonce is secret. (Honest users generate fresh nonces.)

```
lemma no_nonce_NS1_NS2:
 "Nprg
  ∈ Always {s. Crypt (pubK C) {|NA', Nonce NA|} ∈ parts (spies s) -->
               Crypt (pubK B) {|Nonce NA, Agent A|} ∈ parts (spies s) -->
               Nonce NA ∈ analz (spies s)}"
apply ns_induct
apply (blast intro: analz_insertI)+
```

done

Adding it to the claset slows down proofs...

```
lemmas no_nonce_NS1_NS2_reachable =
       no_nonce_NS1_NS2 [THEN Always_Collect_reachableD, rule_format]
```

Unicity for NS1: nonce NA identifies agents A and B

```
lemma unique_NA_lemma:
     "Nprg
  ∈ Always {s. Nonce NA ∉ analz (spies s) -->
               Crypt(pubK B) {|Nonce NA, Agent A|} ∈ parts(spies s) -->
               Crypt(pubK B') {|Nonce NA, Agent A'|} ∈ parts(spies s) -->
               A=A' & B=B'}"
apply ns_induct
apply auto
```

Fake, NS1 are non-trivial

done

Unicity for NS1: nonce NA identifies agents A and B

```
lemma unique_NA:
     "[| Crypt(pubK B)  {|Nonce NA, Agent A|} ∈ parts(spies s);
         Crypt(pubK B') {|Nonce NA, Agent A'|} ∈ parts(spies s);
         Nonce NA ∉ analz (spies s);
         s ∈ reachable Nprg |]
      ==> A=A' & B=B'"
by (blast dest: unique_NA_lemma [THEN Always_Collect_reachableD])
```

Secrecy: Spy does not see the nonce sent in msg NS1 if A and B are secure

```
lemma Spy_not_see_NA:
     "[| A ∉ bad;  B ∉ bad |]
  ==> Nprg ∈ Always
              {s. Says A B (Crypt(pubK B) {|Nonce NA, Agent A|}) ∈ set s
                  --> Nonce NA ∉ analz (spies s)}"
apply ns_induct
```

NS3

```
prefer 4 apply (blast intro: no_nonce_NS1_NS2_reachable)
```

NS2

```
prefer 3 apply (blast dest: unique_NA)
```

NS1

```
prefer 2 apply blast
```

Fake

```
apply spy_analz
done
```

Authentication for A: if she receives message 2 and has used NA to start a run, then B has sent message 2.

```
lemma A_trusts_NS2:
 "[| A ∉ bad;  B ∉ bad |]
  ==> Nprg ∈ Always
              {s. Says A B (Crypt(pubK B) {|Nonce NA, Agent A|}) ∈ set s &
                  Crypt(pubK A) {|Nonce NA, Nonce NB|} ∈ parts (knows Spy s)
         --> Says B A (Crypt(pubK A) {|Nonce NA, Nonce NB|}) ∈ set s}"

apply (insert Spy_not_see_NA [of A B NA], simp, ns_induct)
apply (auto dest: unique_NA)
done
```

If the encrypted message appears then it originated with Alice in NS1

```
lemma B_trusts_NS1:
     "Nprg ∈ Always
              {s. Nonce NA ∉ analz (spies s) -->
                  Crypt (pubK B) {|Nonce NA, Agent A|} ∈ parts (spies s)
         --> Says A B (Crypt (pubK B) {|Nonce NA, Agent A|}) ∈ set s}"
apply ns_induct
apply blast
done
```

19.3 Authenticity properties obtained from NS2

Unicity for NS2: nonce NB identifies nonce NA and agent A. Proof closely follows that of *unique_NA*.

```
lemma unique_NB_lemma:
 "Nprg
  ∈ Always {s. Nonce NB ∉ analz (spies s)  -->
               Crypt (pubK A) {|Nonce NA, Nonce NB|} ∈ parts (spies s) -->
               Crypt(pubK A') {|Nonce NA', Nonce NB|} ∈ parts(spies s) -->
               A=A' & NA=NA'}"
apply ns_induct
apply auto
```

Fake, NS2 are non-trivial

```
done

lemma unique_NB:
     "[| Crypt(pubK A) {|Nonce NA, Nonce NB|} ∈ parts(spies s);
         Crypt(pubK A') {|Nonce NA', Nonce NB|} ∈ parts(spies s);
         Nonce NB ∉ analz (spies s);
         s ∈ reachable Nprg |]
      ==> A=A' & NA=NA'"
apply (blast dest: unique_NB_lemma [THEN Always_Collect_reachableD])
done
```

NB remains secret PROVIDED Alice never responds with round 3

```
lemma Spy_not_see_NB:
     "[| A ∉ bad;  B ∉ bad |]
  ==> Nprg ∈ Always
              {s. Says B A (Crypt (pubK A) {|Nonce NA, Nonce NB|}) ∈ set s &
                  (∀C. Says A C (Crypt (pubK C) (Nonce NB)) ∉ set s)
```

```
                --> Nonce NB ∉ analz (spies s)}"
apply ns_induct
apply (simp_all (no_asm_simp) add: all_conj_distrib)
```

NS3: because NB determines A

```
prefer 4 apply (blast dest: unique_NB)
```

NS2: by freshness and unicity of NB

```
prefer 3 apply (blast intro: no_nonce_NS1_NS2_reachable)
```

NS1: by freshness

```
prefer 2 apply blast
```

Fake

```
apply spy_analz
done
```

Authentication for B: if he receives message 3 and has used NB in message 2, then A has sent message 3–to somebody....

```
lemma B_trusts_NS3:
     "[| A ∉ bad;  B ∉ bad |]
  ==> Nprg ∈ Always
              {s. Crypt (pubK B) (Nonce NB) ∈ parts (spies s) &
                  Says B A  (Crypt (pubK A) {|Nonce NA, Nonce NB|}) ∈ set s
                  --> (∃C. Says A C (Crypt (pubK C) (Nonce NB)) ∈ set s)}"

apply (insert Spy_not_see_NB [of A B NA NB], simp, ns_induct)
apply (simp_all (no_asm_simp) add: ex_disj_distrib)
apply auto
```

NS3: because NB determines A. This use of `unique_NB` is robust.

```
apply (blast intro: unique_NB [THEN conjunct1])
done
```

Can we strengthen the secrecy theorem? NO

```
lemma "[| A ∉ bad;  B ∉ bad |]
  ==> Nprg ∈ Always
              {s. Says B A (Crypt (pubK A) {|Nonce NA, Nonce NB|}) ∈ set s
                  --> Nonce NB ∉ analz (spies s)}"
apply ns_induct
apply auto
```

Fake

```
apply spy_analz
```

NS2: by freshness and unicity of NB

```
 apply (blast intro: no_nonce_NS1_NS2_reachable)
```

NS3: unicity of NB identifies A and NA, but not B

```
apply (frule_tac A'=A in Says_imp_spies [THEN parts.Inj, THEN unique_NB])
apply (erule Says_imp_spies [THEN parts.Inj], auto)
apply (rename_tac s B' C)
```

This is the attack!

```
1. ⋀s B' C.
      ⟦A ∉ bad; B ∉ bad; s ∈ reachable Nprg;
       Says A C (Crypt (pubK C) {|Nonce NA, Agent A|}) ∈ set s;
       Says B' A (Crypt (pubK A) {|Nonce NA, Nonce NB|}) ∈ set s;
       C ∈ bad;
       Says B A (Crypt (pubK A) {|Nonce NA, Nonce NB|}) ∈ set s;
       Nonce NB ∉ analz (knows Spy s)⟧
      ⟹ False
```

oops

end

theory *Handshake* **imports** *"../UNITY_Main"* **begin**

record *state* =
  BB :: bool
  NF :: nat
  NG :: nat

definition

  *cmdF :: "(state*state) set"*
  where *"cmdF = {(s,s'). s' = s (|NF:= Suc(NF s), BB:=False|) & BB s}"*

definition
  F :: "state program"
  where *"F = mk_total_program ({s. NF s = 0 & BB s}, {cmdF}, UNIV)"*

definition

  *cmdG :: "(state*state) set"*
  where *"cmdG = {(s,s'). s' = s (|NG:= Suc(NG s), BB:=True|) & ~ BB s}"*

definition
  G :: "state program"
  where *"G = mk_total_program ({s. NG s = 0 & BB s}, {cmdG}, UNIV)"*

definition

  invFG :: "state set"
  where *"invFG = {s. NG s <= NF s & NF s <= Suc (NG s) & (BB s = (NF s = NG s))}"*

declare *F_def [THEN def_prg_Init, simp]*
        G_def [THEN def_prg_Init, simp]

        cmdF_def [THEN def_act_simp, simp]
        cmdG_def [THEN def_act_simp, simp]

```
        invFG_def [THEN def_set_simp, simp]


lemma invFG: "(F ⊔ G) ∈ Always invFG"
apply (rule AlwaysI)
apply force
apply (rule constrains_imp_Constrains [THEN StableI])
apply auto
 apply (unfold F_def, safety)
apply (unfold G_def, safety)
done

lemma lemma2_1: "(F ⊔ G) ∈ ({s. NF s = k} - {s. BB s}) LeadsTo
                            ({s. NF s = k} Int {s. BB s})"
apply (rule stable_Join_ensures1[THEN leadsTo_Basis, THEN leadsTo_imp_LeadsTo])
 apply (unfold F_def, safety)
apply (unfold G_def, ensures_tac "cmdG")
done

lemma lemma2_2: "(F ⊔ G) ∈ ({s. NF s = k} Int {s. BB s}) LeadsTo
                            {s. k < NF s}"
apply (rule stable_Join_ensures2[THEN leadsTo_Basis, THEN leadsTo_imp_LeadsTo])
 apply (unfold F_def, ensures_tac "cmdF")
apply (unfold G_def, safety)
done

lemma progress: "(F ⊔ G) ∈ UNIV LeadsTo {s. m < NF s}"
apply (rule LeadsTo_weaken_R)
apply (rule_tac f = "NF" and l = "Suc m" and B = "{}"
       in GreaterThan_bounded_induct)

apply (auto intro!: lemma2_1 lemma2_2
            intro: LeadsTo_Trans LeadsTo_Diff simp add: vimage_def)
done

end
```

20 A Family of Similar Counters: Original Version

```
theory Counter imports "../UNITY_Main" begin


datatype name = C | c nat
type_synonym state = "name=>int"

primrec sum  :: "[nat,state]=>int" where

  "sum 0 s = 0"
| "sum (Suc i) s = s (c i) + sum i s"

primrec sumj :: "[nat, nat, state]=>int" where
```

```
  "sumj 0 i s = 0"
| "sumj (Suc n) i s = (if n=i then sum n s else s (c n) + sumj n i s)"

type_synonym command = "(state*state)set"

definition a :: "nat=>command" where
 "a i = {(s, s'). s'=s(c i:= s (c i) + 1, C:= s C + 1)}"

definition Component :: "nat => state program" where
  "Component i =
    mk_total_program({s. s C = 0 & s (c i) = 0}, {a i},
                     ⋃G ∈ preserves (%s. s (c i)). Acts G)"


declare Component_def [THEN def_prg_Init, simp]
declare a_def [THEN def_act_simp, simp]


lemma sum_upd_gt: "I<n ==> sum I (s(c n := x)) = sum I s"
  by (induct I) auto


lemma sum_upd_eq: "sum I (s(c I := x)) = sum I s"
  by (induct I) (auto simp add: sum_upd_gt [unfolded fun_upd_def])

lemma sum_upd_C: "sum I (s(C := x)) = sum I s"
  by (induct I) auto

lemma sumj_upd_ci: "sumj I i (s(c i := x)) = sumj I i s"
  by (induct I) (auto simp add: sum_upd_eq [unfolded fun_upd_def])

lemma sumj_upd_C: "sumj I i (s(C := x)) = sumj I i s"
  by (induct I) (auto simp add: sum_upd_C [unfolded fun_upd_def])

lemma sumj_sum_gt: "I<i ==> sumj I i s = sum I s"
  by (induct I) auto

lemma sumj_sum_eq: "(sumj I I s = sum I s)"
  by (induct I) (auto simp add: sumj_sum_gt)

lemma sum_sumj: "i<I ==> sum I s = s (c i) +  sumj I i s"
  by (induct I) (auto simp add: linorder_neq_iff sumj_sum_eq)


lemma p2: "Component i ∈ stable {s. s C = s (c i) + k}"
by (simp add: Component_def, safety)

lemma p3: "Component i ∈ stable {s. ∀v. v≠c i & v≠C --> s v = k v}"
by (simp add: Component_def, safety)


lemma p2_p3_lemma1:
```

```
"(∀k. Component i ∈ stable ({s. s C = s (c i) + sumj I i k}
                  ∩ {s. ∀v. v≠c i & v≠C --> s v = k v}))
   = (Component i ∈ stable {s. s C = s (c i) + sumj I i s})"
apply (simp add: Component_def mk_total_program_def)
apply (auto simp add: constrains_def stable_def sumj_upd_C sumj_upd_ci)
done

lemma p2_p3_lemma2:
"∀k. Component i ∈ stable ({s. s C = s (c i) + sumj I i k} Int
                           {s. ∀v. v≠c i & v≠C --> s v = k v})"
by (blast intro: stable_Int [OF p2 p3])

lemma p2_p3: "Component i ∈ stable {s.  s C = s (c i) + sumj I i s}"
by (auto intro!: p2_p3_lemma2 simp add: p2_p3_lemma1 [symmetric])



lemma sum_0': "(⋀i. i < I ==> s (c i) = 0) ==> sum I s = 0"
  by (induct I) auto


lemma safety:
     "0<I ==> (⨅i ∈ {i. i<I}. Component i) ∈ invariant {s. s C = sum I s}"
apply (simp (no_asm) add: invariant_def JN_stable sum_sumj)
apply (force intro: p2_p3 sum_0')
done

end
```

21 A Family of Similar Counters: Version with Compatibility

```
theory Counterc imports "../UNITY_Main" begin

typedecl state

consts
  C :: "state=>int"
  c :: "state=>nat=>int"

primrec sum  :: "[nat,state]=>int" where

  "sum 0 s = 0"
| "sum (Suc i) s = (c s) i + sum i s"

primrec sumj :: "[nat, nat, state]=>int" where
  "sumj 0 i s = 0"
| "sumj (Suc n) i s = (if n=i then sum n s else (c s) n + sumj n i s)"

type_synonym command = "(state*state)set"

definition a :: "nat=>command" where
 "a i = {(s, s'). (c s') i = (c s) i + 1 & (C s') = (C s) + 1}"
```

definition *Component :: "nat => state program"* **where**
"Component i = mk_total_program({s. C s = 0 & (c s) i = 0},
{a i},
⋃G ∈ preserves (%s. (c s) i). Acts G)"

declare *Component_def [THEN def_prg_Init, simp]*
declare *Component_def [THEN def_prg_AllowedActs, simp]*
declare *a_def [THEN def_act_simp, simp]*

lemma *sum_sumj_eq1: "I<i ==> sum I s = sumj I i s"*
by *(induct I) auto*

lemma *sum_sumj_eq2: "i<I ==> sum I s = c s i + sumj I i s"*
by *(induct I) (auto simp add: linorder_neq_iff sum_sumj_eq1)*

lemma *sum_ext: "(⋀i. i<I ⟹ c s' i = c s i) ==> sum I s' = sum I s"*
by *(induct I) auto*

lemma *sumj_ext: "(⋀j. j<I ==> j≠i ==> c s' j = c s j) ==> sumj I i s'*
= sumj I i s"
by *(induct I) (auto intro!: sum_ext)*

lemma *sum0: "(⋀i. i<I ==> c s i = 0) ==> sum I s = 0"*
by *(induct I) auto*

lemma *Component_ok_iff:*
"(Component i ok G) =
(G ∈ preserves (%s. c s i) & Component i ∈ Allowed G)"
apply *(auto simp add: ok_iff_Allowed Component_def [THEN def_total_prg_Allowed])*
done
declare *Component_ok_iff [iff]*
declare *OK_iff_ok [iff]*
declare *preserves_def [simp]*

lemma *p2: "Component i ∈ stable {s. C s = (c s) i + k}"*
by *(simp add: Component_def, safety)*

lemma *p3:*
"[| OK I Component; i∈I |]
==> Component i ∈ stable {s. ∀j∈I. j≠i --> c s j = c k j}"
apply *simp*
apply *(unfold Component_def mk_total_program_def)*
apply *(simp (no_asm_use) add: stable_def constrains_def)*
apply *blast*
done

lemma *p2_p3_lemma1:*
```
     "[| OK {i. i<I} Component; i<I |] ==>
      ∀k. Component i ∈ stable ({s. C s = c s i + sumj I i k} Int
                                {s. ∀j∈{i. i<I}. j≠i --> c s j = c k j})"
```
by *(blast intro: stable_Int [OF p2 p3])*

lemma *p2_p3_lemma2:*
```
     "(∀k. F ∈ stable ({s. C s = (c s) i + sumj I i k} Int
                       {s. ∀j∈{i. i<I}. j≠i --> c s j = c k j}))
      ==> (F ∈ stable {s. C s = c s i + sumj I i s})"
```
apply *(simp add: constrains_def stable_def)*
apply *(force intro!: sumj_ext)*
done

lemma *p2_p3:*
```
     "[| OK {i. i<I} Component; i<I |]
      ==> Component i ∈ stable {s. C s = c s i + sumj I i s}"
```
by *(blast intro: p2_p3_lemma1 [THEN p2_p3_lemma2])*

lemma *safety:*
```
     "[| 0<I; OK {i. i<I} Component |]
      ==> (⨆i∈{i. i<I}. (Component i)) ∈ invariant {s. C s = sum I s}"
```
apply *(simp (no_asm) add: invariant_def JN_stable sum_sumj_eq2)*
apply *(auto intro!: sum0 p2_p3)*
done

end

theory *PriorityAux*
imports *"../UNITY_Main"*
begin

typedecl *vertex*

definition *symcl :: "(vertex*vertex)set=>(vertex*vertex)set"* **where**
  "symcl r == r ∪ (r⁻¹)"
    — symmetric closure: removes the orientation of a relation

definition *neighbors :: "[vertex, (vertex*vertex)set]=>vertex set"* **where**
  "neighbors i r == ((r ∪ r⁻¹)``{i}) - {i}"
    — Neighbors of a vertex i

definition *R :: "[vertex, (vertex*vertex)set]=>vertex set"* **where**
  "R i r == r``{i}"

definition *A :: "[vertex, (vertex*vertex)set]=>vertex set"* **where**
  "A i r == (r⁻¹)``{i}"

definition *reach :: "[vertex, (vertex*vertex)set]=> vertex set"* **where**
  "reach i r == (r⁺)``{i}"

— reachable and above vertices: the original notation was R* and A*

definition *above :: "[vertex, (vertex*vertex)set]=> vertex set"* **where**
"above i r == ((r^{-1})$^{+}$)``{i}"

definition *reverse :: "[vertex, (vertex*vertex) set]=>(vertex*vertex)set"* **where**
"reverse i r == (r - {(x,y). x=i | y=i} ∩ r) ∪ ({(x,y). x=i|y=i} ∩ r)$^{-1}$"

definition *derive1 :: "[vertex, (vertex*vertex)set, (vertex*vertex)set]=>bool"*
where
— The original definition
"derive1 i r q == symcl r = symcl q &
(∀k k'. k≠i & k'≠i -->((k,k') ∈ r) = ((k,k') ∈ q)) ∧
A i r = {} & R i q = {}"

definition *derive :: "[vertex, (vertex*vertex)set, (vertex*vertex)set]=>bool"*
where
— Our alternative definition
"derive i r q == A i r = {} & (q = reverse i r)"

axiomatization where
finite_vertex_univ: "finite (UNIV :: vertex set)"
— we assume that the universe of vertices is finite

declare *derive_def [simp] derive1_def [simp] symcl_def [simp]*
A_def [simp] R_def [simp]
above_def [simp] reach_def [simp]
reverse_def [simp] neighbors_def [simp]

All vertex sets are finite

declare *finite_subset [OF subset_UNIV finite_vertex_univ, iff]*

and relatons over vertex are finite too

lemmas *finite_UNIV_Prod =*
finite_Prod_UNIV [OF finite_vertex_univ finite_vertex_univ]

declare *finite_subset [OF subset_UNIV finite_UNIV_Prod, iff]*

lemma *image0_trancl_iff_image0_r: "((r^{+})``{i} = {}) = (r``{i} = {})"*
apply *auto*
apply *(erule trancl_induct, auto)*
done

lemma *image0_r_iff_image0_trancl: "(r``{i}={}) = (∀x. ((i,x) ∈ r^{+}) = False)"*
apply *auto*
apply *(drule image0_trancl_iff_image0_r [THEN ssubst], auto)*
done

lemma *acyclic_eq_wf: "!!r::(vertex*vertex)set. acyclic r = wf r"*
by *(auto simp add: wf_iff_acyclic_if_finite)*

lemma *derive_derive1_eq: "derive i r q = derive1 i r q"*
by *auto*

lemma *lemma1_a:*
"[| x ∈ reach i q; derive1 k r q |] ==> x≠k --> x ∈ reach i r"
apply *(unfold reach_def)*
apply *(erule ImageE)*
apply *(erule trancl_induct)*
apply *(cases "i=k", simp_all)*
apply *(blast, blast, clarify)*
apply *(drule_tac x = y* **in** *spec)*
apply *(drule_tac x = z* **in** *spec)*
apply *(blast dest: r_into_trancl intro: trancl_trans)*
done

lemma *reach_lemma: "derive k r q ==> reach i q ⊆ (reach i r ∪ {k})"*
apply *clarify*
apply *(drule lemma1_a)*
apply *(auto simp add: derive_derive1_eq*
simp del: reach_def derive_def derive1_def)
done

lemma *reach_above_lemma:*
"(∀i. reach i q ⊆ (reach i r ∪ {k})) =
(∀x. x≠k --> (∀i. i ∉ above x r --> i ∉ above x q))"
by *(auto simp add: trancl_converse)*

lemma *maximal_converse_image0:*
"(z, i) ∈ r^+ ⟹ (∀y. (y, z) ∈ r ⟶ (y,i) ∉ r^+) = ((r^{-1})``{z}={})"
apply *auto*
apply *(frule_tac r = r* **in** *trancl_into_trancl2, auto)*
done

lemma *above_lemma_a:*
"acyclic r ==> A i r≠{}-->(∃j ∈ above i r. A j r = {})"
apply *(simp add: acyclic_eq_wf wf_eq_minimal)*
apply *(drule_tac x = " ((r^{-1})$^+$) ``{i}"* **in** *spec)*
apply *auto*
apply *(simp add: maximal_converse_image0 trancl_converse)*
done

lemma *above_lemma_b:*
"acyclic r ==> above i r≠{}-->(∃j ∈ above i r. above j r = {})"
apply *(drule above_lemma_a)*
apply *(auto simp add: image0_trancl_iff_image0_r)*
done

end

22 The priority system

theory *Priority* **imports** *PriorityAux* **begin**

From Charpentier and Chandy, Examples of Program Composition Illustrating the Use of Universal Properties In J. Rolim (editor), Parallel and Distributed Processing, Spriner LNCS 1586 (1999), pages 1215-1227.

type_synonym *state = "(vertex*vertex)set"*
type_synonym *command = "vertex=>(state*state)set"*

consts
*init :: "(vertex*vertex)set"*
— the initial state

Following the definitions given in section 4.4

definition *highest :: "[vertex, (vertex*vertex)set]=>bool"*
where *"highest i r ⟷ A i r = {}"*
— i has highest priority in r

definition *lowest :: "[vertex, (vertex*vertex)set]=>bool"*
where *"lowest i r ⟷ R i r = {}"*
— i has lowest priority in r

definition *act :: command*
where *"act i = {(s, s'). s'=reverse i s & highest i s}"*

definition *Component :: "vertex=>state program"*
where *"Component i = mk_total_program({init}, {act i}, UNIV)"*
— All components start with the same initial state

Some Abbreviations

definition *Highest :: "vertex=>state set"*
where *"Highest i = {s. highest i s}"*

definition *Lowest :: "vertex=>state set"*
where *"Lowest i = {s. lowest i s}"*

definition *Acyclic :: "state set"*
where *"Acyclic = {s. acyclic s}"*

definition *Maximal :: "state set"*
— Every "above" set has a maximal vertex
where *"Maximal = (⋂i. {s. ~highest i s-->(∃j ∈ above i s. highest j s)})"*

definition *Maximal' :: "state set"*
— Maximal vertex: equivalent definition
where *"Maximal' = (⋂i. Highest i Un (⋃j. {s. j ∈ above i s} Int Highest j))"*

```
definition Safety :: "state set"
  where "Safety = (⋂i. {s. highest i s --> (∀j ∈ neighbors i s. ~highest
j s)})"
```

```
definition system :: "state program"
  where "system = (⨆i. Component i)"
```

```
declare highest_def [simp] lowest_def [simp]
declare Highest_def [THEN def_set_simp, simp]
    and Lowest_def  [THEN def_set_simp, simp]

declare Component_def [THEN def_prg_Init, simp]
declare act_def [THEN def_act_simp, simp]
```

22.1 Component correctness proofs

neighbors is stable

```
lemma Component_neighbors_stable: "Component i ∈ stable {s. neighbors k
s = n}"
by (simp add: Component_def, safety, auto)
```

property 4

```
lemma Component_waits_priority: "Component i ∈ {s. ((i,j) ∈ s) = b} ∩ (-
Highest i) co {s. ((i,j) ∈ s)=b}"
by (simp add: Component_def, safety)
```

property 5: charpentier and Chandy mistakenly express it as 'transient Highest i'. Consider the case where i has neighbors

```
lemma Component_yields_priority:
 "Component i ∈ {s. neighbors i s ≠ {}} Int Highest i
              ensures - Highest i"
apply (simp add: Component_def)
apply (ensures_tac "act i", blast+)
done
```

or better

```
lemma Component_yields_priority': "Component i ∈ Highest i ensures Lowest
i"
apply (simp add: Component_def)
apply (ensures_tac "act i", blast+)
done
```

property 6: Component doesn't introduce cycle

```
lemma Component_well_behaves: "Component i ∈ Highest i co Highest i Un Lowest
i"
by (simp add: Component_def, safety, fast)
```

property 7: local axiom

```
lemma locality: "Component i ∈ stable {s. ∀j k. j≠i & k≠i--> ((j,k) ∈
s) = b j k}"
by (simp add: Component_def, safety)
```

22.2 System properties

property 8: strictly universal

```
lemma Safety: "system ∈ stable Safety"
apply (unfold Safety_def)
apply (rule stable_INT)
apply (simp add: system_def, safety, fast)
done
```

property 13: universal

```
lemma p13: "system ∈ {s. s = q} co {s. s=q} Un {s. ∃i. derive i q s}"
by (simp add: system_def Component_def mk_total_program_def totalize_JN, safety,
blast)
```

property 14: the 'above set' of a Component that hasn't got priority doesn't increase

```
lemma above_not_increase:
     "system ∈ -Highest i Int {s. j∉above i s} co {s. j∉above i s}"
apply (insert reach_lemma [of concl: j])
apply (simp add: system_def Component_def mk_total_program_def totalize_JN,

       safety)
apply (simp add: trancl_converse, blast)
done

lemma above_not_increase':
     "system ∈ -Highest i Int {s. above i s = x} co {s. above i s <= x}"
apply (insert above_not_increase [of i])
apply (simp add: trancl_converse constrains_def, blast)
done
```

p15: universal property: all Components well behave

```
lemma system_well_behaves: "system ∈ Highest i co Highest i Un Lowest i"
  by (simp add: system_def Component_def mk_total_program_def totalize_JN,
safety, auto)


lemma Acyclic_eq: "Acyclic = (⋂i. {s. i∉above i s})"
  by (auto simp add: Acyclic_def acyclic_def trancl_converse)


lemmas system_co =
      constrains_Un [OF above_not_increase [rule_format] system_well_behaves]


lemma Acyclic_stable: "system ∈ stable Acyclic"
apply (simp add: stable_def Acyclic_eq)
apply (auto intro!: constrains_INT system_co [THEN constrains_weaken]
```

```
            simp add: image0_r_iff_image0_trancl trancl_converse)
done


lemma Acyclic_subset_Maximal: "Acyclic <= Maximal"
apply (unfold Acyclic_def Maximal_def, clarify)
apply (drule above_lemma_b, auto)
done
```

property 17: original one is an invariant

```
lemma Acyclic_Maximal_stable: "system ∈ stable (Acyclic Int Maximal)"
by (simp add: Acyclic_subset_Maximal [THEN Int_absorb2] Acyclic_stable)
```

property 5: existential property

```
lemma Highest_leadsTo_Lowest: "system ∈ Highest i leadsTo Lowest i"
apply (simp add: system_def Component_def mk_total_program_def totalize_JN)
apply (ensures_tac "act i", auto)
done
```

a lowest i can never be in any abover set

```
lemma Lowest_above_subset: "Lowest i <= (⋂k. {s. i∉above k s})"
by (auto simp add: image0_r_iff_image0_trancl trancl_converse)
```

property 18: a simpler proof than the original, one which uses psp

```
lemma Highest_escapes_above: "system ∈ Highest i leadsTo (⋂k. {s. i∉above
k s})"
apply (rule leadsTo_weaken_R)
apply (rule_tac [2] Lowest_above_subset)
apply (rule Highest_leadsTo_Lowest)
done

lemma Highest_escapes_above':
     "system ∈ Highest j Int {s. j ∈ above i s} leadsTo {s. j∉above i s}"
by (blast intro: leadsTo_weaken [OF Highest_escapes_above Int_lower1 INT_lower])
```

22.3 The main result: above set decreases

The original proof of the following formula was wrong

```
lemma Highest_iff_above0: "Highest i = {s. above i s ={}}"
by (auto simp add: image0_trancl_iff_image0_r)

lemmas above_decreases_lemma =
     psp [THEN leadsTo_weaken, OF Highest_escapes_above' above_not_increase']



lemma above_decreases:
     "system ∈ (⋃j. {s. above i s = x} Int {s. j ∈ above i s} Int Highest
j)
               leadsTo {s. above i s < x}"
apply (rule leadsTo_UN)
apply (rule single_leadsTo_I, clarify)
```

```
apply (rule_tac x = "above i xa" in above_decreases_lemma)
apply (simp_all (no_asm_use) add: Highest_iff_above0)
apply blast+
done


lemma Maximal_eq_Maximal': "Maximal = Maximal'"
by (unfold Maximal_def Maximal'_def Highest_def, blast)

lemma Acyclic_subset:
   "x≠{} ==>
    Acyclic Int {s. above i s = x} <=
    (⋃j. {s. above i s = x} Int {s. j ∈ above i s} Int Highest j)"
apply (rule_tac B = "Maximal' Int {s. above i s = x}" in subset_trans)
apply (simp (no_asm) add: Maximal_eq_Maximal' [symmetric])
apply (blast intro: Acyclic_subset_Maximal [THEN subsetD])
apply (simp (no_asm) del: above_def add: Maximal'_def Highest_iff_above0)
apply blast
done

lemmas above_decreases' = leadsTo_weaken_L [OF above_decreases Acyclic_subset]
lemmas above_decreases_psp = psp_stable [OF above_decreases' Acyclic_stable]

lemma above_decreases_psp':
"x≠{}==> system ∈ Acyclic Int {s. above i s = x} leadsTo
                  Acyclic Int {s. above i s < x}"
by (erule above_decreases_psp [THEN leadsTo_weaken], blast, auto)


lemmas finite_psubset_induct = wf_finite_psubset [THEN leadsTo_wf_induct]


lemma Progress: "system ∈ Acyclic leadsTo Highest i"
apply (rule_tac f = "%s. above i s" in finite_psubset_induct)
apply (simp del: above_def
            add: Highest_iff_above0 vimage_def finite_psubset_def, clarify)
apply (case_tac "m={}")
apply (rule Int_lower2 [THEN [2] leadsTo_weaken_L])
apply (force simp add: leadsTo_refl)
apply (rule_tac A' = "Acyclic Int {x. above i x < m}" in leadsTo_weaken_R)
apply (blast intro: above_decreases_psp')+
done
```

We have proved all (relevant) theorems given in the paper. We didn't assume any thing about the relation `r`. It is not necessary that `r` be a priority relation as assumed in the original proof. It suffices that we start from a state which is finite and acyclic.

```
end


theory TimerArray imports "../UNITY_Main" begin

type_synonym 'a state = "nat * 'a"
```

```
definition count :: "'a state => nat"
  where "count s = fst s"

definition decr  :: "('a state * 'a state) set"
  where "decr = (UN n uu. {((Suc n, uu), (n,uu))})"

definition Timer :: "'a state program"
  where "Timer = mk_total_program (UNIV, {decr}, UNIV)"


declare Timer_def [THEN def_prg_Init, simp]

declare count_def [simp] decr_def [simp]


lemma Timer_leadsTo_zero: "Timer ∈ UNIV leadsTo {s. count s = 0}"
apply (rule_tac f = count in lessThan_induct, simp)
apply (case_tac "m")
 apply (force intro!: subset_imp_leadsTo)
apply (unfold Timer_def, ensures_tac "decr")
done

lemma Timer_preserves_snd [iff]: "Timer ∈ preserves snd"
apply (rule preservesI)
apply (unfold Timer_def, safety)
done


declare PLam_stable [simp]

lemma TimerArray_leadsTo_zero:
     "finite I
      ⟹ (plam i: I. Timer) ∈ UNIV leadsTo {(s,uu). ∀i∈I. s i = 0}"
apply (erule_tac A'1 = "λi. lift_set i ({0} × UNIV)"
       in finite_stable_completion [THEN leadsTo_weaken])
apply auto

 prefer 2
 apply (simp add: Timer_def, safety)

apply (rule_tac f = "sub i o fst" in lessThan_induct)
apply (case_tac "m")

apply (auto intro: subset_imp_leadsTo
        simp add: insert_absorb
                  lift_set_Un_distrib [symmetric] lessThan_Suc [symmetric]

                Times_Un_distrib1 [symmetric] Times_Diff_distrib1 [symmetric])
apply (rename_tac "n")
apply (rule PLam_leadsTo_Basis)
apply (auto simp add: lessThan_Suc [symmetric])
apply (unfold Timer_def mk_total_program_def, safety)
apply (rule_tac act = decr in totalize_transientI, auto)
done
```

end

23 Progress Set Examples

theory *Progress* **imports** *"../UNITY_Main"* **begin**

23.1 The Composition of Two Single-Assignment Programs

Thesis Section 4.4.2

definition *FF :: "int program"* **where**
"FF = mk_total_program (UNIV, {range (λx. (x, x+1))}, UNIV)"

definition *GG :: "int program"* **where**
*"GG = mk_total_program (UNIV, {range (λx. (x, 2*x))}, UNIV)"*

23.1.1 Calculating *wens_set FF {k..}*

lemma *Domain_actFF: "Domain (range (λx::int. (x, x + 1))) = UNIV"*
by *force*

lemma *FF_eq:*
"FF = mk_program (UNIV, {range (λx. (x, x+1))}, UNIV)"
by *(simp add: FF_def mk_total_program_def totalize_def totalize_act_def*
program_equalityI Domain_actFF)

lemma *wp_actFF:*
"wp (range (λx::int. (x, x + 1))) (atLeast k) = atLeast (k - 1)"
by *(force simp add: wp_def)*

lemma *wens_FF: "wens FF (range (λx. (x, x+1))) (atLeast k) = atLeast (k -*
1)"
by *(force simp add: FF_eq wens_single_eq wp_actFF)*

lemma *single_valued_actFF: "single_valued (range (λx::int. (x, x + 1)))"*
by *(force simp add: single_valued_def)*

lemma *wens_single_finite_FF:*
"wens_single_finite (range (λx. (x, x+1))) (atLeast k) n =
atLeast (k - int n)"
apply *(induct n, simp)*
apply *(force simp add: wens_FF*
def_wens_single_finite_Suc_eq_wens [OF FF_eq single_valued_actFF])
done

lemma *wens_single_FF_eq_UNIV:*
"wens_single (range (λx::int. (x, x + 1))) (atLeast k) = UNIV"
apply *(auto simp add: wens_single_eq_Union)*
apply *(rule_tac x="nat (k-x)"* **in** *exI)*
apply *(simp add: wens_single_finite_FF)*
done

lemma *wens_set_FF:*

```
    "wens_set FF (atLeast k) = insert UNIV (atLeast ` atMost k)"
apply (auto simp add: wens_set_single_eq [OF FF_eq single_valued_actFF]
                      wens_single_FF_eq_UNIV wens_single_finite_FF)
apply (erule notE)
apply (rule_tac x="nat (k-xa)" in range_eqI)
apply (simp add: wens_single_finite_FF)
done
```

23.1.2 Proving *FF ∈ UNIV ⟼ {k..}*

```
lemma atLeast_ensures: "FF ∈ atLeast (k - 1) ensures atLeast (k::int)"
apply (simp add: Progress.wens_FF [symmetric] wens_ensures)
apply (simp add: wens_ensures FF_eq)
done

lemma atLeast_leadsTo: "FF ∈ atLeast (k - int n) leadsTo atLeast (k::int)"
apply (induct n)
 apply (simp_all add: leadsTo_refl)
apply (rule_tac A = "atLeast (k - int n - 1)" in leadsTo_weaken_L)
 apply (blast intro: leadsTo_Trans atLeast_ensures, force)
done

lemma UN_atLeast_UNIV: "(⋃n. atLeast (k - int n)) = UNIV"
apply auto
apply (rule_tac x = "nat (k - x)" in exI, simp)
done

lemma FF_leadsTo: "FF ∈ UNIV leadsTo atLeast (k::int)"
apply (subst UN_atLeast_UNIV [symmetric])
apply (rule leadsTo_UN [OF atLeast_leadsTo])
done
```

Result (4.39): Applying the leadsTo-Join Theorem

```
theorem "FF⊔GG ∈ atLeast 0 leadsTo atLeast (k::int)"
apply (subgoal_tac "FF⊔GG ∈ (atLeast 0 ∩ atLeast 0) leadsTo atLeast k")
 apply simp
apply (rule_tac T = "atLeast 0" in leadsTo_Join)
  apply (rule leadsTo_weaken_L [OF FF_leadsTo], simp)
 apply (simp add: awp_iff_constrains FF_def, safety)
apply (simp add: awp_iff_constrains GG_def wens_set_FF, safety)
done

end
```

24 Common Declarations for Chandy and Charpentier's Allocator

```
theory AllocBase imports "../UNITY_Main" "HOL-Library.Multiset_Order" be-
gin

consts Nclients :: nat

axiomatization NbT :: nat
```

```
  where NbT_pos: "0 < NbT"

abbreviation (input) tokens :: "nat list ⇒ nat"
where
  "tokens ≡ sum_list"

abbreviation (input)
  "bag_of ≡ mset"

lemma sum_fun_mono:
  fixes f :: "nat ⇒ nat"
  shows "(⋀i. i < n ⟹ f i ≤ g i) ⟹ sum f {..<n} ≤ sum g {..<n}"
  by (induct n) (auto simp add: lessThan_Suc add_le_mono)

lemma tokens_mono_prefix: "xs ≤ ys ⟹ tokens xs ≤ tokens ys"
  by (induct ys arbitrary: xs) (auto simp add: prefix_Cons)

lemma mono_tokens: "mono tokens"
  using tokens_mono_prefix by (rule monoI)




lemma bag_of_append [simp]: "bag_of (l@l') = bag_of l + bag_of l'"
  by (fact mset_append)

lemma mono_bag_of: "mono (bag_of :: 'a list => ('a::order) multiset)"
apply (rule monoI)
apply (unfold prefix_def)
apply (erule genPrefix.induct, simp_all add: add_right_mono)
apply (erule order_trans)
apply simp
done



declare sum.cong [cong]

lemma bag_of_nths_lemma:
     "(∑i∈ A Int lessThan k. {#if i<k then f i else g i#}) =
      (∑i∈ A Int lessThan k. {#f i#})"
by (rule sum.cong, auto)

lemma bag_of_nths:
     "bag_of (nths l A) =
      (∑i∈ A Int lessThan (length l). {# l!i #})"
  by (rule_tac xs = l in rev_induct)
     (simp_all add: nths_append Int_insert_right lessThan_Suc nth_append
                    bag_of_nths_lemma ac_simps)


lemma bag_of_nths_Un_Int:
     "bag_of (nths l (A Un B)) + bag_of (nths l (A Int B)) =
      bag_of (nths l A) + bag_of (nths l B)"
```

```
apply (subgoal_tac "A Int B Int {..<length l} =
                    (A Int {..<length l}) Int (B Int {..<length l}) ")
apply (simp add: bag_of_nths Int_Un_distrib2 sum.union_inter, blast)
done

lemma bag_of_nths_Un_disjoint:
     "A Int B = {}
      ==> bag_of (nths l (A Un B)) =
          bag_of (nths l A) + bag_of (nths l B)"
by (simp add: bag_of_nths_Un_Int [symmetric])

lemma bag_of_nths_UN_disjoint [rule_format]:
     "[| finite I; ∀i∈I. ∀j∈I. i≠j ⟶ A i Int A j = {} |]
      ==> bag_of (nths l (⋃(A ` I))) =
          (∑i∈I. bag_of (nths l (A i)))"
apply (auto simp add: bag_of_nths)
unfolding UN_simps [symmetric]
apply (subst sum.UNION_disjoint)
apply auto
done

end


theory Alloc
imports AllocBase "../PPROD"
begin
```

24.1 State definitions. OUTPUT variables are locals

```
record clientState =
  giv :: "nat list"    — client's INPUT history: tokens GRANTED
  ask :: "nat list"    — client's OUTPUT history: tokens REQUESTED
  rel :: "nat list"    — client's OUTPUT history: tokens RELEASED

record 'a clientState_d =
  clientState +
  dummy :: 'a          — dummy field for new variables

definition
  — DUPLICATED FROM Client.thy, but with "tok" removed
  — Maybe want a special theory section to declare such maps
  non_dummy :: "'a clientState_d => clientState"
  where "non_dummy s = (|giv = giv s, ask = ask s, rel = rel s|)"

definition
  — Renaming map to put a Client into the standard form
  client_map :: "'a clientState_d => clientState*'a"
  where "client_map = funPair non_dummy dummy"


record allocState =
  allocGiv :: "nat => nat list"    — OUTPUT history: source of "giv" for i
  allocAsk :: "nat => nat list"    — INPUT: allocator's copy of "ask" for i
```

```
  allocRel :: "nat => nat list"    — INPUT: allocator's copy of "rel" for i

record 'a allocState_d =
  allocState +
  dummy    :: 'a                  — dummy field for new variables

record 'a systemState =
  allocState +
  client :: "nat => clientState"  — states of all clients
  dummy  :: 'a                    — dummy field for new variables
```

24.1.1 Resource allocation system specification

definition

```
  — spec (1)
  system_safety :: "'a systemState program set"
  where "system_safety =
     Always {s. (∑ i ∈ lessThan Nclients. (tokens o giv o sub i o client)s)
     ≤ NbT + (∑ i ∈ lessThan Nclients. (tokens o rel o sub i o client)s)}"
```

definition

```
  — spec (2)
  system_progress :: "'a systemState program set"
  where "system_progress = (INT i : lessThan Nclients.
                          INT h.
                            {s. h ≤ (ask o sub i o client)s} LeadsTo
                            {s. h pfixLe (giv o sub i o client) s})"
```

definition

```
  system_spec :: "'a systemState program set"
  where "system_spec = system_safety Int system_progress"
```

24.1.2 Client specification (required)

definition

```
  — spec (3)
  client_increasing :: "'a clientState_d program set"
  where "client_increasing = UNIV guarantees  Increasing ask Int Increasing
rel"
```

definition

```
  — spec (4)
  client_bounded :: "'a clientState_d program set"
  where "client_bounded = UNIV guarantees  Always {s. ∀ elt ∈ set (ask s).
elt ≤ NbT}"
```

definition

```
  — spec (5)
  client_progress :: "'a clientState_d program set"
  where "client_progress =
         Increasing giv  guarantees
         (INT h. {s. h ≤ giv s & h pfixGe ask s}
                 LeadsTo {s. tokens h ≤ (tokens o rel) s})"
```

definition

```
  — spec: preserves part
  client_preserves :: "'a clientState_d program set"
  where "client_preserves = preserves giv Int preserves clientState_d.dummy"

definition
  — environmental constraints
  client_allowed_acts :: "'a clientState_d program set"
  where "client_allowed_acts =
       {F. AllowedActs F =
            insert Id (⋃ (Acts ‘ preserves (funPair rel ask)))}"

definition
  client_spec :: "'a clientState_d program set"
  where "client_spec = client_increasing Int client_bounded Int client_progress
                  Int client_allowed_acts Int client_preserves"
```

24.1.3 Allocator specification (required)

```
definition
  — spec (6)
  alloc_increasing :: "'a allocState_d program set"
  where "alloc_increasing =
         UNIV  guarantees
         (INT i : lessThan Nclients. Increasing (sub i o allocGiv))"

definition
  — spec (7)
  alloc_safety :: "'a allocState_d program set"
  where "alloc_safety =
         (INT i : lessThan Nclients. Increasing (sub i o allocRel))
         guarantees
         Always {s. (∑ i ∈ lessThan Nclients. (tokens o sub i o allocGiv)s)
         ≤ NbT + (∑ i ∈ lessThan Nclients. (tokens o sub i o allocRel)s)}"

definition
  — spec (8)
  alloc_progress :: "'a allocState_d program set"
  where "alloc_progress =
         (INT i : lessThan Nclients. Increasing (sub i o allocAsk) Int
                                     Increasing (sub i o allocRel))
         Int
         Always {s. ∀ i<Nclients.
                    ∀ elt ∈ set ((sub i o allocAsk) s). elt ≤ NbT}
         Int
         (INT i : lessThan Nclients.
          INT h. {s. h ≤ (sub i o allocGiv)s & h pfixGe (sub i o allocAsk)s}
                 LeadsTo
                 {s. tokens h ≤ (tokens o sub i o allocRel)s})
         guarantees
             (INT i : lessThan Nclients.
              INT h. {s. h ≤ (sub i o allocAsk) s}
                     LeadsTo
                     {s. h pfixLe (sub i o allocGiv) s})"
```

definition
— spec: preserves part
```
alloc_preserves :: "'a allocState_d program set"
where "alloc_preserves = preserves allocRel Int preserves allocAsk Int
                         preserves allocState_d.dummy"
```

definition
— environmental constraints
```
alloc_allowed_acts :: "'a allocState_d program set"
where "alloc_allowed_acts =
     {F. AllowedActs F =
          insert Id (⋃(Acts ` (preserves allocGiv)))}"
```

definition
```
alloc_spec :: "'a allocState_d program set"
where "alloc_spec = alloc_increasing Int alloc_safety Int alloc_progress
Int
                  alloc_allowed_acts Int alloc_preserves"
```

24.1.4 Network specification

definition
— spec (9.1)
```
network_ask :: "'a systemState program set"
where "network_ask = (INT i : lessThan Nclients.
                      Increasing (ask o sub i o client)  guarantees
                      ((sub i o allocAsk) Fols (ask o sub i o client)))"
```

definition
— spec (9.2)
```
network_giv :: "'a systemState program set"
where "network_giv = (INT i : lessThan Nclients.
                      Increasing (sub i o allocGiv)
                      guarantees
                      ((giv o sub i o client) Fols (sub i o allocGiv)))"
```

definition
— spec (9.3)
```
network_rel :: "'a systemState program set"
where "network_rel = (INT i : lessThan Nclients.
                      Increasing (rel o sub i o client)
                      guarantees
                      ((sub i o allocRel) Fols (rel o sub i o client)))"
```

definition
— spec: preserves part
```
network_preserves :: "'a systemState program set"
where "network_preserves =
     preserves allocGiv  Int
     (INT i : lessThan Nclients. preserves (rel o sub i o client)  Int
                                 preserves (ask o sub i o client))"
```

definition
— environmental constraints
```
network_allowed_acts :: "'a systemState program set"
```
where `"network_allowed_acts =`
```
     {F. AllowedActs F = insert Id
       (⋃ (Acts ` (preserves allocRel ∩ (⋂i<Nclients.
         preserves (giv ∘ sub i ∘ client)))))}"
```

definition
```
network_spec :: "'a systemState program set"
```
where `"network_spec = network_ask Int network_giv Int`
```
                  network_rel Int network_allowed_acts Int
                  network_preserves"
```

24.1.5 State mappings

definition
```
sysOfAlloc :: "((nat => clientState) * 'a) allocState_d => 'a systemState"
```
where `"sysOfAlloc = (%s. let (cl,xtr) = allocState_d.dummy s`
```
                      in (| allocGiv = allocGiv s,
                            allocAsk = allocAsk s,
                            allocRel = allocRel s,
                            client   = cl,
                            dummy    = xtr|))"
```

definition
```
sysOfClient :: "(nat => clientState) * 'a allocState_d => 'a systemState"
```
where `"sysOfClient = (%(cl,al). (| allocGiv = allocGiv al,`
```
                                  allocAsk = allocAsk al,
                                  allocRel = allocRel al,
                                  client   = cl,
                                  systemState.dummy = allocState_d.dummy al|))"
```

axiomatization `Alloc :: "'a allocState_d program"`
where `Alloc: "Alloc ∈ alloc_spec"`

axiomatization `Client :: "'a clientState_d program"`
where `Client: "Client ∈ client_spec"`

axiomatization `Network :: "'a systemState program"`
where `Network: "Network ∈ network_spec"`

definition `System  :: "'a systemState program"`
where `"System = rename sysOfAlloc Alloc ⊔ Network ⊔`
```
               (rename sysOfClient
                (plam x: lessThan Nclients. rename client_map Client))"
```

declare `subset_preserves_o [THEN [2] rev_subsetD, intro]`
declare `subset_preserves_o [THEN [2] rev_subsetD, simp]`
declare `funPair_o_distrib [simp]`

```
declare Always_INT_distrib [simp]
declare o_apply [simp del]


lemmas [simp] =
  rename_image_constrains
  rename_image_stable
  rename_image_increasing
  rename_image_invariant
  rename_image_Constrains
  rename_image_Stable
  rename_image_Increasing
  rename_image_Always
  rename_image_leadsTo
  rename_image_LeadsTo
  rename_preserves
  rename_image_preserves
  lift_image_preserves
  bij_image_INT
  bij_is_inj [THEN image_Int]
  bij_image_Collect_eq

ML ‹
(*Splits up conjunctions & intersections: like CONJUNCTS in the HOL system*)
fun list_of_Int th =
    (list_of_Int (th RS conjunct1) @ list_of_Int (th RS conjunct2))
    handle THM _ => (list_of_Int (th RS IntD1) @ list_of_Int (th RS IntD2))
    handle THM _ => (list_of_Int (th RS @{thm INT_D}))
    handle THM _ => (list_of_Int (th RS bspec))
    handle THM _ => [th];
›

lemmas lessThanBspec = lessThan_iff [THEN iffD2, THEN [2] bspec]

attribute_setup normalized = ‹
let
  fun normalized th =
    normalized (th RS spec
      handle THM _ => th RS @{thm lessThanBspec}
      handle THM _ => th RS bspec
      handle THM _ => th RS (@{thm guarantees_INT_right_iff} RS iffD1))
    handle THM _ => th;
in
  Scan.succeed (Thm.rule_attribute [] (K normalized))
end
›


ML ‹
fun record_auto_tac ctxt =
  let val ctxt' =
    ctxt addSWrapper Record.split_wrapper
    addsimps
       [@{thm sysOfAlloc_def}, @{thm sysOfClient_def},
```

```
        @{thm client_map_def}, @{thm non_dummy_def}, @{thm funPair_def},
        @{thm o_apply}, @{thm Let_def}]
  in auto_tac ctxt' end;

›

method_setup record_auto = ‹Scan.succeed (SIMPLE_METHOD o record_auto_tac)›

lemma inj_sysOfAlloc [iff]: "inj sysOfAlloc"
  apply (unfold sysOfAlloc_def Let_def)
  apply (rule inj_onI)
  apply record_auto
  done
```

We need the inverse; also having it simplifies the proof of surjectivity

```
lemma inv_sysOfAlloc_eq [simp]: "!!s. inv sysOfAlloc s =
             (| allocGiv = allocGiv s,
                allocAsk = allocAsk s,
                allocRel = allocRel s,
                allocState_d.dummy = (client s, dummy s) |)"
  apply (rule inj_sysOfAlloc [THEN inv_f_eq])
  apply record_auto
  done

lemma surj_sysOfAlloc [iff]: "surj sysOfAlloc"
  apply (simp add: surj_iff_all)
  apply record_auto
  done

lemma bij_sysOfAlloc [iff]: "bij sysOfAlloc"
  apply (blast intro: bijI)
  done
```

24.1.6 bijectivity of *sysOfClient*

```
lemma inj_sysOfClient [iff]: "inj sysOfClient"
  apply (unfold sysOfClient_def)
  apply (rule inj_onI)
  apply record_auto
  done

lemma inv_sysOfClient_eq [simp]: "!!s. inv sysOfClient s =
             (client s,
              (| allocGiv = allocGiv s,
                 allocAsk = allocAsk s,
                 allocRel = allocRel s,
                 allocState_d.dummy = systemState.dummy s|) )"
  apply (rule inj_sysOfClient [THEN inv_f_eq])
  apply record_auto
  done

lemma surj_sysOfClient [iff]: "surj sysOfClient"
  apply (simp add: surj_iff_all)
  apply record_auto
```

done

lemma *bij_sysOfClient [iff]: "bij sysOfClient"*
apply *(blast intro: bijI)*
done

24.1.7 bijectivity of *client_map*

lemma *inj_client_map [iff]: "inj client_map"*
apply *(unfold inj_on_def)*
apply *record_auto*
done

lemma *inv_client_map_eq [simp]: "!!s. inv client_map s =*
(%(x,y).(|giv = giv x, ask = ask x, rel = rel x,
clientState_d.dummy = y|)) s"
apply *(rule inj_client_map [THEN inv_f_eq])*
apply *record_auto*
done

lemma *surj_client_map [iff]: "surj client_map"*
apply *(simp add: surj_iff_all)*
apply *record_auto*
done

lemma *bij_client_map [iff]: "bij client_map"*
apply *(blast intro: bijI)*
done

o-simprules for *client_map*

lemma *fst_o_client_map: "fst o client_map = non_dummy"*
apply *(unfold client_map_def)*
apply *(rule fst_o_funPair)*
done

ML ‹*ML_Thms.bind_thms ("fst_o_client_map'", make_o_equivs* ***context*** *@{thm fst_o_client_map})*›
declare *fst_o_client_map' [simp]*

lemma *snd_o_client_map: "snd o client_map = clientState_d.dummy"*
apply *(unfold client_map_def)*
apply *(rule snd_o_funPair)*
done

ML ‹*ML_Thms.bind_thms ("snd_o_client_map'", make_o_equivs* ***context*** *@{thm snd_o_client_map})*›
declare *snd_o_client_map' [simp]*

24.2 o-simprules for *sysOfAlloc* [MUST BE AUTOMATED]

lemma *client_o_sysOfAlloc: "client o sysOfAlloc = fst o allocState_d.dummy*
"
apply *record_auto*
done

ML ‹ML_Thms.bind_thms ("client_o_sysOfAlloc'", make_o_equivs *context* @{thm client_o_sysOfAlloc})›
declare client_o_sysOfAlloc' [simp]

lemma allocGiv_o_sysOfAlloc_eq: "allocGiv o sysOfAlloc = allocGiv"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("allocGiv_o_sysOfAlloc_eq'", make_o_equivs *context* @{thm allocGiv_o_sysOfAlloc_eq})›
declare allocGiv_o_sysOfAlloc_eq' [simp]

lemma allocAsk_o_sysOfAlloc_eq: "allocAsk o sysOfAlloc = allocAsk"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("allocAsk_o_sysOfAlloc_eq'", make_o_equivs *context* @{thm allocAsk_o_sysOfAlloc_eq})›
declare allocAsk_o_sysOfAlloc_eq' [simp]

lemma allocRel_o_sysOfAlloc_eq: "allocRel o sysOfAlloc = allocRel"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("allocRel_o_sysOfAlloc_eq'", make_o_equivs *context* @{thm allocRel_o_sysOfAlloc_eq})›
declare allocRel_o_sysOfAlloc_eq' [simp]

24.3 o-simprules for sysOfClient [MUST BE AUTOMATED]

lemma client_o_sysOfClient: "client o sysOfClient = fst"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("client_o_sysOfClient'", make_o_equivs *context* @{thm client_o_sysOfClient})›
declare client_o_sysOfClient' [simp]

lemma allocGiv_o_sysOfClient_eq: "allocGiv o sysOfClient = allocGiv o snd
"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("allocGiv_o_sysOfClient_eq'", make_o_equivs *context* @{thm allocGiv_o_sysOfClient_eq})›
declare allocGiv_o_sysOfClient_eq' [simp]

lemma allocAsk_o_sysOfClient_eq: "allocAsk o sysOfClient = allocAsk o snd
"
apply record_auto
done

ML ‹ML_Thms.bind_thms ("allocAsk_o_sysOfClient_eq'", make_o_equivs *context* @{thm allocAsk_o_sysOfClient_eq})›

```
declare allocAsk_o_sysOfClient_eq' [simp]

lemma allocRel_o_sysOfClient_eq: "allocRel o sysOfClient = allocRel o snd
"
  apply record_auto
  done

ML ‹ML_Thms.bind_thms ("allocRel_o_sysOfClient_eq'", make_o_equivs context
@{thm allocRel_o_sysOfClient_eq})›
declare allocRel_o_sysOfClient_eq' [simp]

lemma allocGiv_o_inv_sysOfAlloc_eq: "allocGiv o inv sysOfAlloc = allocGiv"
  apply (simp add: o_def)
  done

ML ‹ML_Thms.bind_thms ("allocGiv_o_inv_sysOfAlloc_eq'", make_o_equivs con-
text @{thm allocGiv_o_inv_sysOfAlloc_eq})›
declare allocGiv_o_inv_sysOfAlloc_eq' [simp]

lemma allocAsk_o_inv_sysOfAlloc_eq: "allocAsk o inv sysOfAlloc = allocAsk"
  apply (simp add: o_def)
  done

ML ‹ML_Thms.bind_thms ("allocAsk_o_inv_sysOfAlloc_eq'", make_o_equivs con-
text @{thm allocAsk_o_inv_sysOfAlloc_eq})›
declare allocAsk_o_inv_sysOfAlloc_eq' [simp]

lemma allocRel_o_inv_sysOfAlloc_eq: "allocRel o inv sysOfAlloc = allocRel"
  apply (simp add: o_def)
  done

ML ‹ML_Thms.bind_thms ("allocRel_o_inv_sysOfAlloc_eq'", make_o_equivs con-
text @{thm allocRel_o_inv_sysOfAlloc_eq})›
declare allocRel_o_inv_sysOfAlloc_eq' [simp]

lemma rel_inv_client_map_drop_map: "(rel o inv client_map o drop_map i o
inv sysOfClient) =
      rel o sub i o client"
  apply (simp add: o_def drop_map_def)
  done

ML ‹ML_Thms.bind_thms ("rel_inv_client_map_drop_map'", make_o_equivs con-
text @{thm rel_inv_client_map_drop_map})›
declare rel_inv_client_map_drop_map [simp]

lemma ask_inv_client_map_drop_map: "(ask o inv client_map o drop_map i o
inv sysOfClient) =
      ask o sub i o client"
  apply (simp add: o_def drop_map_def)
  done

ML ‹ML_Thms.bind_thms ("ask_inv_client_map_drop_map'", make_o_equivs con-
text @{thm ask_inv_client_map_drop_map})›
declare ask_inv_client_map_drop_map [simp]
```

Client : <unfolded specification>

```
lemmas client_spec_simps =
  client_spec_def client_increasing_def client_bounded_def
  client_progress_def client_allowed_acts_def client_preserves_def
  guarantees_Int_right

ML ‹
val [Client_Increasing_ask, Client_Increasing_rel,
     Client_Bounded, Client_Progress, Client_AllowedActs,
     Client_preserves_giv, Client_preserves_dummy] =
        @{thm Client} |> simplify (context addsimps @{thms client_spec_simps})
               |> list_of_Int;

ML_Thms.bind_thm ("Client_Increasing_ask", Client_Increasing_ask);
ML_Thms.bind_thm ("Client_Increasing_rel", Client_Increasing_rel);
ML_Thms.bind_thm ("Client_Bounded", Client_Bounded);
ML_Thms.bind_thm ("Client_Progress", Client_Progress);
ML_Thms.bind_thm ("Client_AllowedActs", Client_AllowedActs);
ML_Thms.bind_thm ("Client_preserves_giv", Client_preserves_giv);
ML_Thms.bind_thm ("Client_preserves_dummy", Client_preserves_dummy);
›

declare
  Client_Increasing_ask [iff]
  Client_Increasing_rel [iff]
  Client_Bounded [iff]
  Client_preserves_giv [iff]
  Client_preserves_dummy [iff]
```

Network : <unfolded specification>

```
lemmas network_spec_simps =
  network_spec_def network_ask_def network_giv_def
  network_rel_def network_allowed_acts_def network_preserves_def
  ball_conj_distrib

ML ‹
val [Network_Ask, Network_Giv, Network_Rel, Network_AllowedActs,
     Network_preserves_allocGiv, Network_preserves_rel,
     Network_preserves_ask]  =
        @{thm Network} |> simplify (context addsimps @{thms network_spec_simps})
                |> list_of_Int;

ML_Thms.bind_thm ("Network_Ask", Network_Ask);
ML_Thms.bind_thm ("Network_Giv", Network_Giv);
ML_Thms.bind_thm ("Network_Rel", Network_Rel);
ML_Thms.bind_thm ("Network_AllowedActs", Network_AllowedActs);
ML_Thms.bind_thm ("Network_preserves_allocGiv", Network_preserves_allocGiv);
ML_Thms.bind_thm ("Network_preserves_rel", Network_preserves_rel);
ML_Thms.bind_thm ("Network_preserves_ask", Network_preserves_ask);
›

declare Network_preserves_allocGiv [iff]

declare
```

```
  Network_preserves_rel [simp]
  Network_preserves_ask [simp]

declare
  Network_preserves_rel [simplified o_def, simp]
  Network_preserves_ask [simplified o_def, simp]
```

Alloc : <unfolded specification>

```
lemmas alloc_spec_simps =
  alloc_spec_def alloc_increasing_def alloc_safety_def
  alloc_progress_def alloc_allowed_acts_def alloc_preserves_def

ML ‹
val [Alloc_Increasing_0, Alloc_Safety, Alloc_Progress, Alloc_AllowedActs,
     Alloc_preserves_allocRel, Alloc_preserves_allocAsk,
     Alloc_preserves_dummy] =
        @{thm Alloc} |> simplify (context addsimps @{thms alloc_spec_simps})
              |> list_of_Int;

ML_Thms.bind_thm ("Alloc_Increasing_0", Alloc_Increasing_0);
ML_Thms.bind_thm ("Alloc_Safety", Alloc_Safety);
ML_Thms.bind_thm ("Alloc_Progress", Alloc_Progress);
ML_Thms.bind_thm ("Alloc_AllowedActs", Alloc_AllowedActs);
ML_Thms.bind_thm ("Alloc_preserves_allocRel", Alloc_preserves_allocRel);
ML_Thms.bind_thm ("Alloc_preserves_allocAsk", Alloc_preserves_allocAsk);
ML_Thms.bind_thm ("Alloc_preserves_dummy", Alloc_preserves_dummy);
›
```

Strip off the INT in the guarantees postcondition

```
lemmas Alloc_Increasing = Alloc_Increasing_0 [normalized]

declare
  Alloc_preserves_allocRel [iff]
  Alloc_preserves_allocAsk [iff]
  Alloc_preserves_dummy [iff]
```

24.4 Components Lemmas [MUST BE AUTOMATED]

```
lemma Network_component_System: "Network ⊔
      ((rename sysOfClient
        (plam x: (lessThan Nclients). rename client_map Client)) ⊔
       rename sysOfAlloc Alloc)
      = System"
  by (simp add: System_def Join_ac)

lemma Client_component_System: "(rename sysOfClient
       (plam x: (lessThan Nclients). rename client_map Client)) ⊔
      (Network ⊔ rename sysOfAlloc Alloc)  =  System"
  by (simp add: System_def Join_ac)

lemma Alloc_component_System: "rename sysOfAlloc Alloc ⊔
       ((rename sysOfClient (plam x: (lessThan Nclients). rename client_map
Client)) ⊔
        Network)  =  System"
```

```
  by (simp add: System_def Join_ac)

declare
  Client_component_System [iff]
  Network_component_System [iff]
  Alloc_component_System [iff]
```

* These preservation laws should be generated automatically *

```
lemma Client_Allowed [simp]: "Allowed Client = preserves rel Int preserves
ask"
  by (auto simp add: Allowed_def Client_AllowedActs safety_prop_Acts_iff)

lemma Network_Allowed [simp]: "Allowed Network =
       preserves allocRel Int
       (INT i: lessThan Nclients. preserves(giv o sub i o client))"
  by (auto simp add: Allowed_def Network_AllowedActs safety_prop_Acts_iff)

lemma Alloc_Allowed [simp]: "Allowed Alloc = preserves allocGiv"
  by (auto simp add: Allowed_def Alloc_AllowedActs safety_prop_Acts_iff)
```

needed in *rename_client_map_tac*

```
lemma OK_lift_rename_Client [simp]: "OK I (%i. lift i (rename client_map
Client))"
  apply (rule OK_lift_I)
  apply auto
  apply (drule_tac w1 = rel in subset_preserves_o [THEN [2] rev_subsetD])
  apply (drule_tac [2] w1 = ask in subset_preserves_o [THEN [2] rev_subsetD])
  apply (auto simp add: o_def split_def)
  done

lemma fst_lift_map_eq_fst [simp]: "fst (lift_map i x) i = fst x"
apply (insert fst_o_lift_map [of i])
apply (drule fun_cong [where x=x])
apply (simp add: o_def)
done

lemma fst_o_lift_map' [simp]:
     "(f ∘ sub i ∘ fst ∘ lift_map i ∘ g) = f o fst o g"
apply (subst fst_o_lift_map [symmetric])
apply (simp only: o_assoc)
done
```

ML

```
‹
fun rename_client_map_tac ctxt =
  EVERY [
    simp_tac (ctxt addsimps [@{thm rename_guarantees_eq_rename_inv}]) 1,
    resolve_tac ctxt @{thms guarantees_PLam_I} 1,
    assume_tac ctxt 2,
         (*preserves: routine reasoning*)
    asm_simp_tac (ctxt addsimps [@{thm lift_preserves_sub}]) 2,
         (*the guarantee for  "lift i (rename client_map Client)" *)
```

```
    asm_simp_tac
        (ctxt addsimps [@{thm lift_guarantees_eq_lift_inv},
                        @{thm rename_guarantees_eq_rename_inv},
                        @{thm bij_imp_bij_inv}, @{thm surj_rename},
                        @{thm inv_inv_eq}]) 1,
    asm_simp_tac
        (ctxt addsimps [@{thm o_def}, @{thm non_dummy_def}, @{thm guarantees_Int_right}])
1]
›

method_setup rename_client_map = ‹
  Scan.succeed (fn ctxt => SIMPLE_METHOD (rename_client_map_tac ctxt))
›
```

Lifting *Client_Increasing* to *systemState*

```
lemma rename_Client_Increasing: "i ∈ I
      ==> rename sysOfClient (plam x: I. rename client_map Client) ∈
            UNIV  guarantees
            Increasing (ask o sub i o client) Int
            Increasing (rel o sub i o client)"
  by rename_client_map

lemma preserves_sub_fst_lift_map: "[| F ∈ preserves w; i ≠ j |]
      ==> F ∈ preserves (sub i o fst o lift_map j o funPair v w)"
  apply (auto simp add: lift_map_def split_def linorder_neq_iff o_def)
  apply (drule_tac [!] subset_preserves_o [THEN [2] rev_subsetD])
  apply (auto simp add: o_def)
  done

lemma client_preserves_giv_oo_client_map: "[| i < Nclients; j < Nclients
|]
      ==> Client ∈ preserves (giv o sub i o fst o lift_map j o client_map)"
  apply (cases "i=j")
  apply (simp, simp add: o_def non_dummy_def)
  apply (drule Client_preserves_dummy [THEN preserves_sub_fst_lift_map])
  apply (drule_tac [!] subset_preserves_o [THEN [2] rev_subsetD])
  apply (simp add: o_def client_map_def)
  done

lemma rename_sysOfClient_ok_Network:
  "rename sysOfClient (plam x: lessThan Nclients. rename client_map Client)
    ok Network"
  by (auto simp add: ok_iff_Allowed client_preserves_giv_oo_client_map)

lemma rename_sysOfClient_ok_Alloc:
  "rename sysOfClient (plam x: lessThan Nclients. rename client_map Client)
    ok rename sysOfAlloc Alloc"
  by (simp add: ok_iff_Allowed)

lemma rename_sysOfAlloc_ok_Network: "rename sysOfAlloc Alloc ok Network"
  by (simp add: ok_iff_Allowed)

declare
  rename_sysOfClient_ok_Network [iff]
```

```
  rename_sysOfClient_ok_Alloc [iff]
  rename_sysOfAlloc_ok_Network [iff]
```

The "ok" laws, re-oriented. But not sure this works: theorem `ok_commute` is needed below

```
declare
  rename_sysOfClient_ok_Network [THEN ok_sym, iff]
  rename_sysOfClient_ok_Alloc [THEN ok_sym, iff]
  rename_sysOfAlloc_ok_Network [THEN ok_sym]

lemma System_Increasing: "i < Nclients
      ==> System ∈ Increasing (ask o sub i o client) Int
                   Increasing (rel o sub i o client)"
  apply (rule component_guaranteesD [OF rename_Client_Increasing Client_component_System])
  apply auto
  done

lemmas rename_guarantees_sysOfAlloc_I =
  bij_sysOfAlloc [THEN rename_rename_guarantees_eq, THEN iffD2]



lemmas rename_Alloc_Increasing =
  Alloc_Increasing
    [THEN rename_guarantees_sysOfAlloc_I,
     simplified surj_rename o_def sub_apply
                rename_image_Increasing bij_sysOfAlloc
                allocGiv_o_inv_sysOfAlloc_eq']

lemma System_Increasing_allocGiv:
     "i < Nclients ⟹ System ∈ Increasing (sub i o allocGiv)"
  apply (unfold System_def)
  apply (simp add: o_def)
  apply (rule rename_Alloc_Increasing [THEN guarantees_Join_I1, THEN guaranteesD])
  apply auto
  done


ML ‹
ML_Thms.bind_thms ("System_Increasing'", list_of_Int @{thm System_Increasing})
›

declare System_Increasing' [intro!]
```

Follows consequences. The "Always (INT ...) formulation expresses the general safety property and allows it to be combined using `Always_Int_rule` below.

```
lemma System_Follows_rel:
  "i < Nclients ==> System ∈ ((sub i o allocRel) Fols (rel o sub i o client))"
  apply (auto intro!: Network_Rel [THEN component_guaranteesD])
  apply (simp add: ok_commute [of Network])
  done

lemma System_Follows_ask:
  "i < Nclients ==> System ∈ ((sub i o allocAsk) Fols (ask o sub i o client))"
```

```
  apply (auto intro!: Network_Ask [THEN component_guaranteesD])
  apply (simp add: ok_commute [of Network])
  done

lemma System_Follows_allocGiv:
  "i < Nclients ==> System ∈ (giv o sub i o client) Fols (sub i o allocGiv)"
  apply (auto intro!: Network_Giv [THEN component_guaranteesD]
    rename_Alloc_Increasing [THEN component_guaranteesD])
  apply (simp_all add: o_def non_dummy_def ok_commute [of Network])
  apply (auto intro!: rename_Alloc_Increasing [THEN component_guaranteesD])
  done


lemma Always_giv_le_allocGiv: "System ∈ Always (INT i: lessThan Nclients.
                      {s. (giv o sub i o client) s ≤ (sub i o allocGiv) s})"
  apply auto
  apply (erule System_Follows_allocGiv [THEN Follows_Bounded])
  done


lemma Always_allocAsk_le_ask: "System ∈ Always (INT i: lessThan Nclients.
                      {s. (sub i o allocAsk) s ≤ (ask o sub i o client) s})"
  apply auto
  apply (erule System_Follows_ask [THEN Follows_Bounded])
  done


lemma Always_allocRel_le_rel: "System ∈ Always (INT i: lessThan Nclients.
                      {s. (sub i o allocRel) s ≤ (rel o sub i o client) s})"
  by (auto intro!: Follows_Bounded System_Follows_rel)
```

24.5 Proof of the safety property (1)

safety (1), step 1 is *System_Follows_rel*

safety (1), step 2

```
lemmas System_Increasing_allocRel = System_Follows_rel [THEN Follows_Increasing1]
```

safety (1), step 3

```
lemma System_sum_bounded:
    "System ∈ Always {s. (∑ i ∈ lessThan Nclients. (tokens o sub i o allocGiv)
s)
           ≤ NbT + (∑ i ∈ lessThan Nclients. (tokens o sub i o allocRel)
s)}"
  apply (simp add: o_apply)
  apply (insert Alloc_Safety [THEN rename_guarantees_sysOfAlloc_I])
  apply (simp add: o_def)
  apply (erule component_guaranteesD)
  apply (auto simp add: System_Increasing_allocRel [simplified sub_apply o_def])
  done
```

Follows reasoning

```
lemma Always_tokens_giv_le_allocGiv: "System ∈ Always (INT i: lessThan Nclients.
```

```
                        {s. (tokens o giv o sub i o client) s
                         ≤ (tokens o sub i o allocGiv) s})"
  apply (rule Always_giv_le_allocGiv [THEN Always_weaken])
  apply (auto intro: tokens_mono_prefix simp add: o_apply)
  done

lemma Always_tokens_allocRel_le_rel: "System ∈ Always (INT i: lessThan Nclients.
                        {s. (tokens o sub i o allocRel) s
                         ≤ (tokens o rel o sub i o client) s})"
  apply (rule Always_allocRel_le_rel [THEN Always_weaken])
  apply (auto intro: tokens_mono_prefix simp add: o_apply)
  done
```

safety (1), step 4 (final result!)

```
theorem System_safety: "System ∈ system_safety"
  apply (unfold system_safety_def)
  apply (tactic ‹resolve_tac context [Always_Int_rule [@{thm System_sum_bounded},
    @{thm Always_tokens_giv_le_allocGiv}, @{thm Always_tokens_allocRel_le_rel}]
RS
    @{thm Always_weaken}] 1›)
  apply auto
  apply (rule sum_fun_mono [THEN order_trans])
  apply (drule_tac [2] order_trans)
  apply (rule_tac [2] add_le_mono [OF order_refl sum_fun_mono])
  prefer 3 apply assumption
  apply auto
  done
```

24.6 Proof of the progress property (2)

progress (2), step 1 is `System_Follows_ask` and `System_Follows_rel`

progress (2), step 2; see also `System_Increasing_allocRel`

```
lemmas System_Increasing_allocAsk =  System_Follows_ask [THEN Follows_Increasing1]
```

progress (2), step 3: lifting `Client_Bounded` to systemState

```
lemma rename_Client_Bounded: "i ∈ I
    ==> rename sysOfClient (plam x: I. rename client_map Client) ∈
          UNIV  guarantees
          Always {s. ∀elt ∈ set ((ask o sub i o client) s). elt ≤ NbT}"
  using image_cong_simp [cong del] by rename_client_map

lemma System_Bounded_ask: "i < Nclients
     ==> System ∈ Always
                  {s. ∀elt ∈ set ((ask o sub i o client) s). elt ≤ NbT}"
  apply (rule component_guaranteesD [OF rename_Client_Bounded Client_component_System])
  apply auto
  done

lemma Collect_all_imp_eq: "{x. ∀y. P y ⟶ Q x y} = (INT y: {y. P y}. {x.
Q x y})"
  apply blast
  done
```

progress (2), step 4

lemma *System_Bounded_allocAsk: "System ∈ Always {s. ∀i<Nclients. ∀elt ∈ set ((sub i o allocAsk) s). elt ≤ NbT}"*
apply *(auto simp add: Collect_all_imp_eq)*
apply *(tactic ‹resolve_tac context [Always_Int_rule [@{thm Always_allocAsk_le_ask}, @{thm System_Bounded_ask}] RS @{thm Always_weaken}] 1›)*
apply *(auto dest: set_mono)*
done

progress (2), step 5 is *System_Increasing_allocGiv*

progress (2), step 6

lemmas *System_Increasing_giv = System_Follows_allocGiv [THEN Follows_Increasing1]*

lemma *rename_Client_Progress: "i ∈ I*
==> rename sysOfClient (plam x: I. rename client_map Client)
∈ Increasing (giv o sub i o client)
guarantees
(INT h. {s. h ≤ (giv o sub i o client) s &
h pfixGe (ask o sub i o client) s}
LeadsTo {s. tokens h ≤ (tokens o rel o sub i o client) s})"
supply *image_cong_simp [cong del]*
apply *rename_client_map*
apply *(simp add: Client_Progress [simplified o_def])*
done

progress (2), step 7

lemma *System_Client_Progress:*
"System ∈ (INT i : (lessThan Nclients).
INT h. {s. h ≤ (giv o sub i o client) s &
h pfixGe (ask o sub i o client) s}
LeadsTo {s. tokens h ≤ (tokens o rel o sub i o client) s})"
apply *(rule INT_I)*

apply *(rule component_guaranteesD [OF rename_Client_Progress Client_component_System])*
apply *(auto simp add: System_Increasing_giv)*
done

lemmas *System_lemma1 =*
Always_LeadsToD [OF System_Follows_ask [THEN Follows_Bounded]
System_Follows_allocGiv [THEN Follows_LeadsTo]]

lemmas *System_lemma2 =*
PSP_Stable [OF System_lemma1
System_Follows_ask [THEN Follows_Increasing1, THEN IncreasingD]]

lemma *System_lemma3: "i < Nclients*
==> System ∈ {s. h ≤ (sub i o allocGiv) s &
h pfixGe (sub i o allocAsk) s}

```
                  LeadsTo
                  {s. h ≤ (giv o sub i o client) s &
                      h pfixGe (ask o sub i o client) s}"
  apply (rule single_LeadsTo_I)
  apply (rule_tac k1 = h and x1 = "(sub i o allocAsk) s"
         in System_lemma2 [THEN LeadsTo_weaken])
  apply auto
  apply (blast intro: trans_Ge [THEN trans_genPrefix, THEN transD] prefix_imp_pfixGe)
  done
```

progress (2), step 8: Client i's "release" action is visible system-wide

```
lemma System_Alloc_Client_Progress: "i < Nclients
      ==> System ∈ {s. h ≤ (sub i o allocGiv) s &
                       h pfixGe (sub i o allocAsk) s}
                  LeadsTo {s. tokens h ≤ (tokens o sub i o allocRel) s}"
  apply (rule LeadsTo_Trans)
   prefer 2
   apply (drule System_Follows_rel [THEN
     mono_tokens [THEN mono_Follows_o, THEN [2] rev_subsetD],
     THEN Follows_LeadsTo])
   apply (simp add: o_assoc)
  apply (rule LeadsTo_Trans)
   apply (cut_tac [2] System_Client_Progress)
   prefer 2
   apply (blast intro: LeadsTo_Basis)
  apply (erule System_lemma3)
  done
```

Lifting `Alloc_Progress` up to the level of systemState

progress (2), step 9

```
lemma System_Alloc_Progress:
 "System ∈ (INT i : (lessThan Nclients).
            INT h. {s. h ≤ (sub i o allocAsk) s}
                   LeadsTo {s. h pfixLe (sub i o allocGiv) s})"
  apply (simp only: o_apply sub_def)
  apply (insert Alloc_Progress [THEN rename_guarantees_sysOfAlloc_I])
  apply (simp add: o_def del: INT_iff)
  apply (drule component_guaranteesD)
  apply (auto simp add:
    System_Increasing_allocRel [simplified sub_apply o_def]
    System_Increasing_allocAsk [simplified sub_apply o_def]
    System_Bounded_allocAsk [simplified sub_apply o_def]
    System_Alloc_Client_Progress [simplified sub_apply o_def])
  done
```

progress (2), step 10 (final result!)

```
lemma System_Progress: "System ∈ system_progress"
  apply (unfold system_progress_def)
  apply (cut_tac System_Alloc_Progress)
  apply auto
  apply (blast intro: LeadsTo_Trans
    System_Follows_allocGiv [THEN Follows_LeadsTo_pfixLe]
    System_Follows_ask [THEN Follows_LeadsTo])
```

```
  done


theorem System_correct: "System ∈ system_spec"
  apply (unfold system_spec_def)
  apply (blast intro: System_safety System_Progress)
  done
```

Some obsolete lemmas

```
lemma non_dummy_eq_o_funPair: "non_dummy = (% (g,a,r). (| giv = g, ask =
a, rel = r |)) o
                               (funPair giv (funPair ask rel))"
  apply (rule ext)
  apply (auto simp add: o_def non_dummy_def)
  done

lemma preserves_non_dummy_eq: "(preserves non_dummy) =
      (preserves rel Int preserves ask Int preserves giv)"
  apply (simp add: non_dummy_eq_o_funPair)
  apply auto
    apply (drule_tac w1 = rel in subset_preserves_o [THEN [2] rev_subsetD])
    apply (drule_tac [2] w1 = ask in subset_preserves_o [THEN [2] rev_subsetD])
    apply (drule_tac [3] w1 = giv in subset_preserves_o [THEN [2] rev_subsetD])
    apply (auto simp add: o_def)
  done
```

Could go to Extend.ML

```
lemma bij_fst_inv_inv_eq: "bij f ⟹ fst (inv (%(x, u). inv f x) z) = f z"
  apply (rule fst_inv_equalityI)
   apply (rule_tac f = "%z. (f z, h z)" for h in surjI)
   apply (simp add: bij_is_inj inv_f_f)
  apply (simp add: bij_is_surj surj_f_inv_f)
  done

end
```

25 Implementation of a multiple-client allocator from a single-client allocator

```
theory AllocImpl imports AllocBase "../Follows" "../PPROD" begin




record 'b merge =
  In   :: "nat => 'b list"
  Out  :: "'b list"
  iOut :: "nat list"

record ('a,'b) merge_d =
  "'b merge" +
```

```
  dummy :: 'a

definition non_dummy :: "('a,'b) merge_d => 'b merge" where
    "non_dummy s = (|In = In s, Out = Out s, iOut = iOut s|)"

record 'b distr =
  In  :: "'b list"
  iIn :: "nat list"
  Out :: "nat => 'b list"

record ('a,'b) distr_d =
  "'b distr" +
  dummy :: 'a

record allocState =
  giv :: "nat list"
  ask :: "nat list"
  rel :: "nat list"

record 'a allocState_d =
  allocState +
  dummy    :: 'a

record 'a systemState =
  allocState +
  mergeRel :: "nat merge"
  mergeAsk :: "nat merge"
  distr    :: "nat distr"
  dummy    :: 'a
```

definition

```
  merge_increasing :: "('a,'b) merge_d program set"
  where "merge_increasing =
         UNIV guarantees (Increasing merge.Out) Int (Increasing merge.iOut)"
```

definition

```
  merge_eqOut :: "('a,'b) merge_d program set"
  where "merge_eqOut =
         UNIV guarantees
         Always {s. length (merge.Out s) = length (merge.iOut s)}"
```

definition

```
  merge_bounded :: "('a,'b) merge_d program set"
  where "merge_bounded =
         UNIV guarantees
         Always {s. ∀elt ∈ set (merge.iOut s). elt < Nclients}"
```

definition

```
merge_follows :: "('a,'b) merge_d program set"
where "merge_follows =
       (⋂i ∈ lessThan Nclients. Increasing (sub i o merge.In))
       guarantees
       (⋂i ∈ lessThan Nclients.
        (%s. nths (merge.Out s)
                    {k. k < size(merge.iOut s) & merge.iOut s! k = i})
        Fols (sub i o merge.In))"
```

definition

```
merge_preserves :: "('a,'b) merge_d program set"
where "merge_preserves = preserves merge.In Int preserves merge_d.dummy"
```

definition

```
merge_allowed_acts :: "('a,'b) merge_d program set"
where "merge_allowed_acts =
     {F. AllowedActs F =
          insert Id (⋃ (Acts ' preserves (funPair merge.Out iOut)))}"
```

definition

```
merge_spec :: "('a,'b) merge_d program set"
where "merge_spec = merge_increasing Int merge_eqOut Int merge_bounded Int
                merge_follows Int merge_allowed_acts Int merge_preserves"
```

definition

```
distr_follows :: "('a,'b) distr_d program set"
where "distr_follows =
       Increasing distr.In Int Increasing distr.iIn Int
       Always {s. ∀elt ∈ set (distr.iIn s). elt < Nclients}
       guarantees
       (⋂i ∈ lessThan Nclients.
        (sub i o distr.Out) Fols
        (%s. nths (distr.In s)
                    {k. k < size(distr.iIn s) & distr.iIn s ! k = i}))"
```

definition

```
distr_allowed_acts :: "('a,'b) distr_d program set"
where "distr_allowed_acts =
     {D. AllowedActs D = insert Id (⋃(Acts ' (preserves distr.Out)))}"
```

definition

```
distr_spec :: "('a,'b) distr_d program set"
where "distr_spec = distr_follows Int distr_allowed_acts"
```

definition

```
  alloc_increasing :: "'a allocState_d program set"
  where "alloc_increasing = UNIV  guarantees  Increasing giv"
```

definition

```
  alloc_safety :: "'a allocState_d program set"
  where "alloc_safety =
         Increasing rel
         guarantees  Always {s. tokens (giv s) ≤ NbT + tokens (rel s)}"
```

definition

```
  alloc_progress :: "'a allocState_d program set"
  where "alloc_progress =
         Increasing ask Int Increasing rel Int
         Always {s. ∀elt ∈ set (ask s). elt ≤ NbT}
         Int
         (⋂h. {s. h ≤ giv s & h pfixGe (ask s)}
                 LeadsTo
                 {s. tokens h ≤ tokens (rel s)})
         guarantees  (⋂h. {s. h ≤ ask s} LeadsTo {s. h pfixLe giv s})"
```

definition

```
  alloc_preserves :: "'a allocState_d program set"
  where "alloc_preserves = preserves rel Int
                           preserves ask Int
                           preserves allocState_d.dummy"
```

definition

```
  alloc_allowed_acts :: "'a allocState_d program set"
  where "alloc_allowed_acts =
       {F. AllowedActs F = insert Id (⋃(Acts ` (preserves giv)))}"
```

definition

```
  alloc_spec :: "'a allocState_d program set"
  where "alloc_spec = alloc_increasing Int alloc_safety Int alloc_progress
Int
                    alloc_allowed_acts Int alloc_preserves"
```

locale *Merge* =

```
  fixes M :: "('a,'b::order) merge_d program"
  assumes
    Merge_spec:  "M  ∈ merge_spec"
```

locale *Distrib* =

```
  fixes D :: "('a,'b::order) distr_d program"
  assumes
    Distrib_spec:  "D ∈ distr_spec"
```

```
declare subset_preserves_o [THEN subsetD, intro]
declare funPair_o_distrib [simp]
declare Always_INT_distrib [simp]
declare o_apply [simp del]
```

25.1 Theorems for Merge

```
context Merge
begin

lemma Merge_Allowed:
     "Allowed M = (preserves merge.Out) Int (preserves merge.iOut)"
apply (cut_tac Merge_spec)
apply (auto simp add: merge_spec_def merge_allowed_acts_def Allowed_def
                      safety_prop_Acts_iff)
done

lemma M_ok_iff [iff]:
     "M ok G = (G ∈ preserves merge.Out & G ∈ preserves merge.iOut &
                    M ∈ Allowed G)"
by (auto simp add: Merge_Allowed ok_iff_Allowed)


lemma Merge_Always_Out_eq_iOut:
     "[| G ∈ preserves merge.Out; G ∈ preserves merge.iOut; M ∈ Allowed G
|]
      ==> M ⊔ G ∈ Always {s. length (merge.Out s) = length (merge.iOut s)}"
apply (cut_tac Merge_spec)
apply (force dest: guaranteesD simp add: merge_spec_def merge_eqOut_def)
done

lemma Merge_Bounded:
     "[| G ∈ preserves merge.iOut; G ∈ preserves merge.Out; M ∈ Allowed G
|]
      ==> M ⊔ G ∈ Always {s. ∀elt ∈ set (merge.iOut s). elt < Nclients}"
apply (cut_tac Merge_spec)
apply (force dest: guaranteesD simp add: merge_spec_def merge_bounded_def)
done

lemma Merge_Bag_Follows_lemma:
     "[| G ∈ preserves merge.iOut; G ∈ preserves merge.Out; M ∈ Allowed G
|]
  ==> M ⊔ G ∈ Always
         {s. (∑ i ∈ lessThan Nclients. bag_of (nths (merge.Out s)
                                {k. k < length (iOut s) & iOut s ! k = i}))
=
             (bag_of o merge.Out) s}"
apply (rule Always_Compl_Un_eq [THEN iffD1])
apply (blast intro: Always_Int_I [OF Merge_Always_Out_eq_iOut Merge_Bounded])
apply (rule UNIV_AlwaysI, clarify)
apply (subst bag_of_nths_UN_disjoint [symmetric])
  apply (simp)
```

```
 apply blast
apply (simp add: set_conv_nth)
apply (subgoal_tac
       "(⋃i ∈ lessThan Nclients. {k. k < length (iOut x) & iOut x ! k = i})
=
       lessThan (length (iOut x))")
 apply (simp (no_asm_simp) add: o_def)
apply blast
done

lemma Merge_Bag_Follows:
     "M ∈ (⋂i ∈ lessThan Nclients. Increasing (sub i o merge.In))
          guarantees
             (bag_of o merge.Out) Fols
             (%s. ∑i ∈ lessThan Nclients. (bag_of o sub i o merge.In) s)"
apply (rule Merge_Bag_Follows_lemma [THEN Always_Follows1, THEN guaranteesI],
auto)
apply (rule Follows_sum)
apply (cut_tac Merge_spec)
apply (auto simp add: merge_spec_def merge_follows_def o_def)
apply (drule guaranteesD)
  prefer 3
  apply (best intro: mono_bag_of [THEN mono_Follows_apply, THEN subsetD],
auto)
done

end
```

25.2 Theorems for Distributor

```
context Distrib
begin

lemma Distr_Increasing_Out:
     "D ∈ Increasing distr.In Int Increasing distr.iIn Int
          Always {s. ∀elt ∈ set (distr.iIn s). elt < Nclients}
          guarantees
          (⋂i ∈ lessThan Nclients. Increasing (sub i o distr.Out))"
apply (cut_tac Distrib_spec)
apply (simp add: distr_spec_def distr_follows_def)
apply clarify
apply (blast intro: guaranteesI Follows_Increasing1 dest: guaranteesD)
done

lemma Distr_Bag_Follows_lemma:
     "[| G ∈ preserves distr.Out;
         D ⊔ G ∈ Always {s. ∀elt ∈ set (distr.iIn s). elt < Nclients} |]
  ==> D ⊔ G ∈ Always
          {s. (∑i ∈ lessThan Nclients. bag_of (nths (distr.In s)
                                {k. k < length (iIn s) & iIn s ! k = i}))
=
              bag_of (nths (distr.In s) (lessThan (length (iIn s))))}"
apply (erule Always_Compl_Un_eq [THEN iffD1])
apply (rule UNIV_AlwaysI, clarify)
```

```
apply (subst bag_of_nths_UN_disjoint [symmetric])
  apply (simp (no_asm))
 apply blast
apply (simp add: set_conv_nth)
apply (subgoal_tac
       "(⋃i ∈ lessThan Nclients. {k. k < length (iIn x) & iIn x ! k = i})
=
        lessThan (length (iIn x))")
 apply (simp (no_asm_simp))
apply blast
done

lemma D_ok_iff [iff]:
     "D ok G = (G ∈ preserves distr.Out & D ∈ Allowed G)"
apply (cut_tac Distrib_spec)
apply (auto simp add: distr_spec_def distr_allowed_acts_def Allowed_def
                      safety_prop_Acts_iff ok_iff_Allowed)
done

lemma Distr_Bag_Follows:
 "D ∈ Increasing distr.In Int Increasing distr.iIn Int
      Always {s. ∀elt ∈ set (distr.iIn s). elt < Nclients}
      guarantees
       (⋂i ∈ lessThan Nclients.
        (%s. ∑i ∈ lessThan Nclients. (bag_of o sub i o distr.Out) s)
        Fols
        (%s. bag_of (nths (distr.In s) (lessThan (length(distr.iIn s))))))"
apply (rule guaranteesI, clarify)
apply (rule Distr_Bag_Follows_lemma [THEN Always_Follows2], auto)
apply (rule Follows_sum)
apply (cut_tac Distrib_spec)
apply (auto simp add: distr_spec_def distr_follows_def o_def)
apply (drule guaranteesD)
  prefer 3
  apply (best intro: mono_bag_of [THEN mono_Follows_apply, THEN subsetD],
auto)
done

end
```

25.3 Theorems for Allocator

```
lemma alloc_refinement_lemma:
     "!!f::nat=>nat. (⋂i ∈ lessThan n. {s. f i ≤ g i s})
      ⊆ {s. (∑x ∈ lessThan n. f x) ≤ (∑x ∈ lessThan n. g x s)}"
apply (induct_tac "n")
apply (auto simp add: lessThan_Suc)
done

lemma alloc_refinement:
"(⋂i ∈ lessThan Nclients. Increasing (sub i o allocAsk) Int
                          Increasing (sub i o allocRel))
  Int
  Always {s. ∀i. i<Nclients -->
```

```
            (∀elt ∈ set ((sub i o allocAsk) s). elt ≤ NbT)}
  Int
  (⋂i ∈ lessThan Nclients.
   ⋂h. {s. h ≤ (sub i o allocGiv)s & h pfixGe (sub i o allocAsk)s}
        LeadsTo {s. tokens h ≤ (tokens o sub i o allocRel)s})
  ⊆
 (⋂i ∈ lessThan Nclients. Increasing (sub i o allocAsk) Int
                          Increasing (sub i o allocRel))
  Int
  Always {s. ∀i. i<Nclients -->
            (∀elt ∈ set ((sub i o allocAsk) s). elt ≤ NbT)}
  Int
  (⋂hf. (⋂i ∈ lessThan Nclients.
         {s. hf i ≤ (sub i o allocGiv)s & hf i pfixGe (sub i o allocAsk)s})
  LeadsTo {s. (∑i ∈ lessThan Nclients. tokens (hf i)) ≤
            (∑i ∈ lessThan Nclients. (tokens o sub i o allocRel)s)})"
apply (auto simp add: ball_conj_distrib)
apply (rename_tac F hf)
apply (rule LeadsTo_weaken_R [OF Finite_stable_completion alloc_refinement_lemma],
blast, blast)
apply (subgoal_tac "F ∈ Increasing (tokens o (sub i o allocRel))")
 apply (simp add: Increasing_def o_assoc)
apply (blast intro: mono_tokens [THEN mono_Increasing_o, THEN subsetD])
done

end
```

26 Distributed Resource Management System: the Client

```
theory Client imports "../Rename" AllocBase begin

type_synonym
  tokbag = nat      — tokbags could be multisets...or any ordered type?

record state =
  giv :: "tokbag list" — input history: tokens granted
  ask :: "tokbag list" — output history: tokens requested
  rel :: "tokbag list" — output history: tokens released
  tok :: tokbag        — current token request

record 'a state_d =
  state +
  dummy :: 'a          — new variables




definition
  rel_act :: "('a state_d * 'a state_d) set"
```

```
  where "rel_act = {(s,s'). 
                ∃nrel. nrel = size (rel s) &
                       s' = s (| rel := rel s @ [giv s!nrel] |) &
                       nrel < size (giv s) &
                       ask s!nrel ≤ giv s!nrel}"
```

definition

```
  tok_act :: "('a state_d * 'a state_d) set"
  where "tok_act = {(s,s'). s'=s | s' = s (|tok := Suc (tok s mod NbT) |)}"
```

definition

```
  ask_act :: "('a state_d * 'a state_d) set"
  where "ask_act = {(s,s'). s'=s |
                       (s' = s (|ask := ask s @ [tok s]|))}"
```

definition

```
  Client :: "'a state_d program"
  where "Client =
       mk_total_program
            ({s. tok s ∈ atMost NbT &
                 giv s = [] & ask s = [] & rel s = []},
             {rel_act, tok_act, ask_act},
             ⋃G ∈ preserves rel Int preserves ask Int preserves tok.
                   Acts G)"
```

definition

```
  non_dummy :: "'a state_d => state"
  where "non_dummy s = (|giv = giv s, ask = ask s, rel = rel s, tok = tok
s|)"
```

definition

```
  client_map :: "'a state_d => state*'a"
  where "client_map = funPair non_dummy dummy"
```

```
declare Client_def [THEN def_prg_Init, simp]
declare Client_def [THEN def_prg_AllowedActs, simp]
declare rel_act_def [THEN def_act_simp, simp]
declare tok_act_def [THEN def_act_simp, simp]
declare ask_act_def [THEN def_act_simp, simp]

lemma Client_ok_iff [iff]:
     "(Client ok G) =
      (G ∈ preserves rel & G ∈ preserves ask & G ∈ preserves tok &
       Client ∈ Allowed G)"
by (auto simp add: ok_iff_Allowed Client_def [THEN def_total_prg_Allowed])
```

Safety property 1: ask, rel are increasing

```
lemma increasing_ask_rel:
     "Client ∈ UNIV guarantees Increasing ask Int Increasing rel"
apply (auto intro!: increasing_imp_Increasing simp add: guar_def preserves_subset_increasing
[THEN subsetD])
apply (auto simp add: Client_def increasing_def)
apply (safety, auto)+
done

declare nth_append [simp] append_one_prefix [simp]
```

Safety property 2: the client never requests too many tokens. With no Substitution Axiom, we must prove the two invariants simultaneously.

```
lemma ask_bounded_lemma:
     "Client ok G
      ==> Client ⊔ G ∈
              Always ({s. tok s ≤ NbT}  Int
                      {s. ∀elt ∈ set (ask s). elt ≤ NbT})"
apply auto
apply (rule invariantI [THEN stable_Join_Always2], force)
 prefer 2
 apply (fast elim!: preserves_subset_stable [THEN subsetD] intro!: stable_Int)

apply (simp add: Client_def, safety)
apply (cut_tac m = "tok s" in NbT_pos [THEN mod_less_divisor], auto)
done
```

export version, with no mention of tok in the postcondition, but unfortunately tok must be declared local.

```
lemma ask_bounded:
     "Client ∈ UNIV guarantees Always {s. ∀elt ∈ set (ask s). elt ≤ NbT}"
apply (rule guaranteesI)
apply (erule ask_bounded_lemma [THEN Always_weaken])
apply (rule Int_lower2)
done
```

** Towards proving the liveness property **

```
lemma stable_rel_le_giv: "Client ∈ stable {s. rel s ≤ giv s}"
by (simp add: Client_def, safety, auto)

lemma Join_Stable_rel_le_giv:
     "[| Client ⊔ G ∈ Increasing giv;  G ∈ preserves rel |]
      ==> Client ⊔ G ∈ Stable {s. rel s ≤ giv s}"
by (rule stable_rel_le_giv [THEN Increasing_preserves_Stable], auto)

lemma Join_Always_rel_le_giv:
     "[| Client ⊔ G ∈ Increasing giv;  G ∈ preserves rel |]
      ==> Client ⊔ G ∈ Always {s. rel s ≤ giv s}"
by (force intro: AlwaysI Join_Stable_rel_le_giv)

lemma transient_lemma:
     "Client ∈ transient {s. rel s = k & k<h & h ≤ giv s & h pfixGe ask s}"
apply (simp add: Client_def mk_total_program_def)
apply (rule_tac act = rel_act in totalize_transientI)
```

```
  apply (auto simp add: Domain_unfold Client_def)
 apply (blast intro: less_le_trans prefix_length_le strict_prefix_length_less)
apply (auto simp add: prefix_def genPrefix_iff_nth Ge_def)
apply (blast intro: strict_prefix_length_less)
done


lemma induct_lemma:
     "[| Client ⊔ G ∈ Increasing giv;  Client ok G |]
  ==> Client ⊔ G ∈ {s. rel s = k & k<h & h ≤ giv s & h pfixGe ask s}
                    LeadsTo {s. k < rel s & rel s ≤ giv s &
                                h ≤ giv s & h pfixGe ask s}"
apply (rule single_LeadsTo_I)
apply (frule increasing_ask_rel [THEN guaranteesD], auto)
apply (rule transient_lemma [THEN Join_transient_I1, THEN transient_imp_leadsTo,
THEN leadsTo_imp_LeadsTo, THEN PSP_Stable, THEN LeadsTo_weaken])
  apply (rule Stable_Int [THEN Stable_Int, THEN Stable_Int])
     apply (erule_tac f = giv and x = "giv s" in IncreasingD)
    apply (erule_tac f = ask and x = "ask s" in IncreasingD)
   apply (erule_tac f = rel and x = "rel s" in IncreasingD)
  apply (erule Join_Stable_rel_le_giv, blast)
 apply (blast intro: order_less_imp_le order_trans)
apply (blast intro: sym order_less_le [THEN iffD2] order_trans
                    prefix_imp_pfixGe pfixGe_trans)
done


lemma rel_progress_lemma:
     "[| Client ⊔ G ∈ Increasing giv;  Client ok G |]
  ==> Client ⊔ G ∈ {s. rel s < h & h ≤ giv s & h pfixGe ask s}
                    LeadsTo {s. h ≤ rel s}"
apply (rule_tac f = "%s. size h - size (rel s) " in LessThan_induct)
apply (auto simp add: vimage_def)
apply (rule single_LeadsTo_I)
apply (rule induct_lemma [THEN LeadsTo_weaken], auto)
 apply (blast intro: order_less_le [THEN iffD2] dest: common_prefix_linear)
apply (drule strict_prefix_length_less)+
apply arith
done


lemma client_progress_lemma:
     "[| Client ⊔ G ∈ Increasing giv;  Client ok G |]
      ==> Client ⊔ G ∈ {s. h ≤ giv s & h pfixGe ask s}
                        LeadsTo {s. h ≤ rel s}"
apply (rule Join_Always_rel_le_giv [THEN Always_LeadsToI], simp_all)
apply (rule LeadsTo_Un [THEN LeadsTo_weaken_L])
  apply (blast intro: rel_progress_lemma)
 apply (rule subset_refl [THEN subset_imp_LeadsTo])
apply (blast intro: order_less_le [THEN iffD2] dest: common_prefix_linear)
done
```

Progress property: all tokens that are given will be released

```
lemma client_progress:
```

```
     "Client ∈
       Increasing giv  guarantees
       (INT h. {s. h ≤ giv s & h pfixGe ask s} LeadsTo {s. h ≤ rel s})"
apply (rule guaranteesI, clarify)
apply (blast intro: client_progress_lemma)
done
```

This shows that the Client won't alter other variables in any state that it is combined with

```
lemma client_preserves_dummy: "Client ∈ preserves dummy"
by (simp add: Client_def preserves_def, clarify, safety, auto)
```

* Obsolete lemmas from first version of the Client *

```
lemma stable_size_rel_le_giv:
     "Client ∈ stable {s. size (rel s) ≤ size (giv s)}"
by (simp add: Client_def, safety, auto)
```

clients return the right number of tokens

```
lemma ok_guar_rel_prefix_giv:
     "Client ∈ Increasing giv  guarantees  Always {s. rel s ≤ giv s}"
apply (rule guaranteesI)
apply (rule AlwaysI, force)
apply (blast intro: Increasing_preserves_Stable stable_rel_le_giv)
done


end
```

27 Projections of State Sets

```
theory Project imports Extend begin

definition projecting :: "['c program => 'c set, 'a*'b => 'c,
                  'a program, 'c program set, 'a program set] => bool" where
    "projecting C h F X' X ==
       ∀G. extend h F⊔G ∈ X' --> F⊔project h (C G) G ∈ X"

definition extending :: "['c program => 'c set, 'a*'b => 'c, 'a program,
                 'c program set, 'a program set] => bool" where
    "extending C h F Y' Y ==
       ∀G. extend h F  ok G --> F⊔project h (C G) G ∈ Y
              --> extend h F⊔G ∈ Y'"

definition subset_closed :: "'a set set => bool" where
    "subset_closed U == ∀A ∈ U. Pow A ⊆ U"


context Extend
begin

lemma project_extend_constrains_I:
     "F ∈ A co B ==> project h C (extend h F) ∈ A co B"
```

```
apply (auto simp add: extend_act_def project_act_def constrains_def)
done
```

27.1 Safety

```
lemma project_unless:
     "[| G ∈ stable C;  project h C G ∈ A unless B |]
      ==> G ∈ (C ∩ extend_set h A) unless (extend_set h B)"
apply (simp add: unless_def project_constrains)
apply (blast dest: stable_constrains_Int intro: constrains_weaken)
done


lemma Join_project_constrains:
     "(F⊔project h C G ∈ A co B)  =
        (extend h F⊔G ∈ (C ∩ extend_set h A) co (extend_set h B) &
         F ∈ A co B)"
apply (simp (no_asm) add: project_constrains)
apply (blast intro: extend_constrains [THEN iffD2, THEN constrains_weaken]

             dest: constrains_imp_subset)
done


lemma Join_project_stable:
     "extend h F⊔G ∈ stable C
      ==> (F⊔project h C G ∈ stable A)  =
          (extend h F⊔G ∈ stable (C ∩ extend_set h A) &
           F ∈ stable A)"
apply (unfold stable_def)
apply (simp only: Join_project_constrains)
apply (blast intro: constrains_weaken dest: constrains_Int)
done


lemma project_constrains_I:
     "extend h F⊔G ∈ extend_set h A co extend_set h B
      ==> F⊔project h C G ∈ A co B"
apply (simp add: project_constrains extend_constrains)
apply (blast intro: constrains_weaken dest: constrains_imp_subset)
done

lemma project_increasing_I:
     "extend h F⊔G ∈ increasing (func o f)
      ==> F⊔project h C G ∈ increasing func"
apply (unfold increasing_def stable_def)
apply (simp del: Join_constrains
            add: project_constrains_I extend_set_eq_Collect)
done

lemma Join_project_increasing:
     "(F⊔project h UNIV G ∈ increasing func)  =
      (extend h F⊔G ∈ increasing (func o f))"
apply (rule iffI)
```

```
apply (erule_tac [2] project_increasing_I)
apply (simp del: Join_stable
            add: increasing_def Join_project_stable)
apply (auto simp add: extend_set_eq_Collect extend_stable [THEN iffD1])
done


lemma project_constrains_D:
     "F⊔project h UNIV G ∈ A co B
      ==> extend h F⊔G ∈ extend_set h A co extend_set h B"
by (simp add: project_constrains extend_constrains)

end
```

27.2 "projecting" and union/intersection (no converses)

```
lemma projecting_Int:
     "[| projecting C h F XA' XA;  projecting C h F XB' XB |]
      ==> projecting C h F (XA' ∩ XB') (XA ∩ XB)"
by (unfold projecting_def, blast)

lemma projecting_Un:
     "[| projecting C h F XA' XA;  projecting C h F XB' XB |]
      ==> projecting C h F (XA' ∪ XB') (XA ∪ XB)"
by (unfold projecting_def, blast)

lemma projecting_INT:
     "[| !!i. i ∈ I ==> projecting C h F (X' i) (X i) |]
      ==> projecting C h F (⋂i ∈ I. X' i) (⋂i ∈ I. X i)"
by (unfold projecting_def, blast)

lemma projecting_UN:
     "[| !!i. i ∈ I ==> projecting C h F (X' i) (X i) |]
      ==> projecting C h F (⋃i ∈ I. X' i) (⋃i ∈ I. X i)"
by (unfold projecting_def, blast)

lemma projecting_weaken:
     "[| projecting C h F X' X;  U'<=X';  X ⊆ U |] ==> projecting C h F U'
U"
by (unfold projecting_def, auto)

lemma projecting_weaken_L:
     "[| projecting C h F X' X;  U'<=X' |] ==> projecting C h F U' X"
by (unfold projecting_def, auto)

lemma extending_Int:
     "[| extending C h F YA' YA;  extending C h F YB' YB |]
      ==> extending C h F (YA' ∩ YB') (YA ∩ YB)"
by (unfold extending_def, blast)

lemma extending_Un:
     "[| extending C h F YA' YA;  extending C h F YB' YB |]
      ==> extending C h F (YA' ∪ YB') (YA ∪ YB)"
by (unfold extending_def, blast)
```

lemma *extending_INT:*
"[| !!i. i ∈ I ==> extending C h F (Y' i) (Y i) |]
==> extending C h F (⋂i ∈ I. Y' i) (⋂i ∈ I. Y i)"
by *(unfold extending_def, blast)*

lemma *extending_UN:*
"[| !!i. i ∈ I ==> extending C h F (Y' i) (Y i) |]
==> extending C h F (⋃i ∈ I. Y' i) (⋃i ∈ I. Y i)"
by *(unfold extending_def, blast)*

lemma *extending_weaken:*
"[| extending C h F Y' Y; Y'<=V'; V ⊆ Y |] ==> extending C h F V' V"
by *(unfold extending_def, auto)*

lemma *extending_weaken_L:*
"[| extending C h F Y' Y; Y'<=V' |] ==> extending C h F V' Y"
by *(unfold extending_def, auto)*

lemma *projecting_UNIV: "projecting C h F X' UNIV"*
by *(simp add: projecting_def)*

context *Extend*
begin

lemma *projecting_constrains:*
"projecting C h F (extend_set h A co extend_set h B) (A co B)"
apply *(unfold projecting_def)*
apply *(blast intro: project_constrains_I)*
done

lemma *projecting_stable:*
"projecting C h F (stable (extend_set h A)) (stable A)"
apply *(unfold stable_def)*
apply *(rule projecting_constrains)*
done

lemma *projecting_increasing:*
"projecting C h F (increasing (func o f)) (increasing func)"
apply *(unfold projecting_def)*
apply *(blast intro: project_increasing_I)*
done

lemma *extending_UNIV: "extending C h F UNIV Y"*
apply *(simp (no_asm) add: extending_def)*
done

lemma *extending_constrains:*
"extending (%G. UNIV) h F (extend_set h A co extend_set h B) (A co B)"
apply *(unfold extending_def)*
apply *(blast intro: project_constrains_D)*
done

lemma *extending_stable:*

```
    "extending (%G. UNIV) h F (stable (extend_set h A)) (stable A)"
apply (unfold stable_def)
apply (rule extending_constrains)
done

lemma extending_increasing:
    "extending (%G. UNIV) h F (increasing (func o f)) (increasing func)"
by (force simp only: extending_def Join_project_increasing)
```

27.3 Reachability and project

```
lemma reachable_imp_reachable_project:
    "[| reachable (extend h F⊔G) ⊆ C;
        z ∈ reachable (extend h F⊔G) |]
     ==> f z ∈ reachable (F⊔project h C G)"
apply (erule reachable.induct)
apply (force intro!: reachable.Init simp add: split_extended_all, auto)
 apply (rule_tac act = x in reachable.Acts)
 apply auto
 apply (erule extend_act_D)
apply (rule_tac act1 = "Restrict C act"
       in project_act_I [THEN [3] reachable.Acts], auto)
done

lemma project_Constrains_D:
    "F⊔project h (reachable (extend h F⊔G)) G ∈ A Co B
     ==> extend h F⊔G ∈ (extend_set h A) Co (extend_set h B)"
apply (unfold Constrains_def)
apply (simp del: Join_constrains
            add: Join_project_constrains, clarify)
apply (erule constrains_weaken)
apply (auto intro: reachable_imp_reachable_project)
done

lemma project_Stable_D:
    "F⊔project h (reachable (extend h F⊔G)) G ∈ Stable A
     ==> extend h F⊔G ∈ Stable (extend_set h A)"
apply (unfold Stable_def)
apply (simp (no_asm_simp) add: project_Constrains_D)
done

lemma project_Always_D:
    "F⊔project h (reachable (extend h F⊔G)) G ∈ Always A
     ==> extend h F⊔G ∈ Always (extend_set h A)"
apply (unfold Always_def)
apply (force intro: reachable.Init simp add: project_Stable_D split_extended_all)
done

lemma project_Increasing_D:
    "F⊔project h (reachable (extend h F⊔G)) G ∈ Increasing func
     ==> extend h F⊔G ∈ Increasing (func o f)"
apply (unfold Increasing_def, auto)
apply (subst extend_set_eq_Collect [symmetric])
apply (simp (no_asm_simp) add: project_Stable_D)
```

done

27.4 Converse results for weak safety: benefits of the argument C

lemma *reachable_project_imp_reachable:*
```
     "[| C ⊆ reachable(extend h F⊔G);
         x ∈ reachable (F⊔project h C G) |]
      ==> ∃y. h(x,y) ∈ reachable (extend h F⊔G)"
```
apply *(erule reachable.induct)*
apply *(force intro: reachable.Init)*
apply *(auto simp add: project_act_def)*
apply *(force del: Id_in_Acts intro: reachable.Acts extend_act_D)+*
done

lemma *project_set_reachable_extend_eq:*
```
     "project_set h (reachable (extend h F⊔G)) =
      reachable (F⊔project h (reachable (extend h F⊔G)) G)"
```
by *(auto dest: subset_refl [THEN reachable_imp_reachable_project]*
subset_refl [THEN reachable_project_imp_reachable])

lemma *reachable_extend_Join_subset:*
```
     "reachable (extend h F⊔G) ⊆ C
      ==> reachable (extend h F⊔G) ⊆
          extend_set h (reachable (F⊔project h C G))"
```
apply *(auto dest: reachable_imp_reachable_project)*
done

lemma *project_Constrains_I:*
```
     "extend h F⊔G ∈ (extend_set h A) Co (extend_set h B)
      ==> F⊔project h (reachable (extend h F⊔G)) G ∈ A Co B"
```
apply *(unfold Constrains_def)*
apply *(simp del: Join_constrains*
add: Join_project_constrains extend_set_Int_distrib)
apply *(rule conjI)*
prefer *2*
apply *(force elim: constrains_weaken_L*
dest!: extend_constrains_project_set
subset_refl [THEN reachable_project_imp_reachable])
apply *(blast intro: constrains_weaken_L)*
done

lemma *project_Stable_I:*
```
     "extend h F⊔G ∈ Stable (extend_set h A)
      ==> F⊔project h (reachable (extend h F⊔G)) G ∈ Stable A"
```
apply *(unfold Stable_def)*
apply *(simp (no_asm_simp) add: project_Constrains_I)*
done

lemma *project_Always_I:*
```
     "extend h F⊔G ∈ Always (extend_set h A)
      ==> F⊔project h (reachable (extend h F⊔G)) G ∈ Always A"
```
apply *(unfold Always_def)*

```
apply (auto simp add: project_Stable_I)
apply (unfold extend_set_def, blast)
done

lemma project_Increasing_I:
    "extend h F⊔G ∈ Increasing (func o f)
     ==> F⊔project h (reachable (extend h F⊔G)) G ∈ Increasing func"
apply (unfold Increasing_def, auto)
apply (simp (no_asm_simp) add: extend_set_eq_Collect project_Stable_I)
done

lemma project_Constrains:
     "(F⊔project h (reachable (extend h F⊔G)) G ∈ A Co B)  =
      (extend h F⊔G ∈ (extend_set h A) Co (extend_set h B))"
apply (blast intro: project_Constrains_I project_Constrains_D)
done

lemma project_Stable:
     "(F⊔project h (reachable (extend h F⊔G)) G ∈ Stable A)  =
      (extend h F⊔G ∈ Stable (extend_set h A))"
apply (unfold Stable_def)
apply (rule project_Constrains)
done

lemma project_Increasing:
   "(F⊔project h (reachable (extend h F⊔G)) G ∈ Increasing func)  =
    (extend h F⊔G ∈ Increasing (func o f))"
apply (simp (no_asm_simp) add: Increasing_def project_Stable extend_set_eq_Collect)
done
```

27.5 A lot of redundant theorems: all are proved to facilitate reasoning about guarantees.

```
lemma projecting_Constrains:
     "projecting (%G. reachable (extend h F⊔G)) h F
                 (extend_set h A Co extend_set h B) (A Co B)"

apply (unfold projecting_def)
apply (blast intro: project_Constrains_I)
done

lemma projecting_Stable:
     "projecting (%G. reachable (extend h F⊔G)) h F
                 (Stable (extend_set h A)) (Stable A)"
apply (unfold Stable_def)
apply (rule projecting_Constrains)
done

lemma projecting_Always:
     "projecting (%G. reachable (extend h F⊔G)) h F
                 (Always (extend_set h A)) (Always A)"
apply (unfold projecting_def)
apply (blast intro: project_Always_I)
done
```

```
lemma projecting_Increasing:
     "projecting (%G. reachable (extend h F⊔G)) h F
                 (Increasing (func o f)) (Increasing func)"
apply (unfold projecting_def)
apply (blast intro: project_Increasing_I)
done

lemma extending_Constrains:
     "extending (%G. reachable (extend h F⊔G)) h F
                  (extend_set h A Co extend_set h B) (A Co B)"
apply (unfold extending_def)
apply (blast intro: project_Constrains_D)
done

lemma extending_Stable:
     "extending (%G. reachable (extend h F⊔G)) h F
                  (Stable (extend_set h A)) (Stable A)"
apply (unfold extending_def)
apply (blast intro: project_Stable_D)
done

lemma extending_Always:
     "extending (%G. reachable (extend h F⊔G)) h F
                  (Always (extend_set h A)) (Always A)"
apply (unfold extending_def)
apply (blast intro: project_Always_D)
done

lemma extending_Increasing:
     "extending (%G. reachable (extend h F⊔G)) h F
                  (Increasing (func o f)) (Increasing func)"
apply (unfold extending_def)
apply (blast intro: project_Increasing_D)
done
```

27.6 leadsETo in the precondition (??)

27.6.1 transient

```
lemma transient_extend_set_imp_project_transient:
     "[| G ∈ transient (C ∩ extend_set h A);  G ∈ stable C |]
      ==> project h C G ∈ transient (project_set h C ∩ A)"
apply (auto simp add: transient_def Domain_project_act)
apply (subgoal_tac "act `` (C ∩ extend_set h A) ⊆ - extend_set h A")
 prefer 2
 apply (simp add: stable_def constrains_def, blast)

apply (erule_tac V = "AA ⊆ -C ∪ BB" for AA BB in thin_rl)
apply (drule bspec, assumption)
apply (simp add: extend_set_def project_act_def, blast)
done
```

```
lemma project_extend_transient_D:
     "project h C (extend h F) ∈ transient (project_set h C ∩ D)
      ==> F ∈ transient (project_set h C ∩ D)"
apply (simp add: transient_def Domain_project_act, safe)
apply blast+
done
```

27.6.2 ensures – a primitive combining progress with safety

```
lemma ensures_extend_set_imp_project_ensures:
     "[| extend h F ∈ stable C;  G ∈ stable C;
         extend h F⊔G ∈ A ensures B;  A-B = C ∩ extend_set h D |]
      ==> F⊔project h C G
            ∈ (project_set h C ∩ project_set h A) ensures (project_set h B)"
apply (simp add: ensures_def project_constrains extend_transient,
       clarify)
apply (intro conjI)

apply (blast intro: extend_stable_project_set
                 [THEN stableD, THEN constrains_Int, THEN constrains_weaken]

             dest!: extend_constrains_project_set equalityD1)

apply (erule stableD [THEN constrains_Int, THEN constrains_weaken])
    apply assumption
   apply (simp (no_asm_use) add: extend_set_def)
   apply blast
 apply (simp add: extend_set_Int_distrib extend_set_Un_distrib)
 apply (blast intro!: extend_set_project_set [THEN subsetD], blast)

apply auto
 prefer 2
 apply (force dest!: equalityD1
              intro: transient_extend_set_imp_project_transient
                          [THEN transient_strengthen])
apply (simp (no_asm_use) add: Int_Diff)
apply (force dest!: equalityD1
             intro: transient_extend_set_imp_project_transient
               [THEN project_extend_transient_D, THEN transient_strengthen])
done
```

Transferring a transient property upwards

```
lemma project_transient_extend_set:
     "project h C G ∈ transient (project_set h C ∩ A - B)
      ==> G ∈ transient (C ∩ extend_set h A - extend_set h B)"
apply (simp add: transient_def project_set_def extend_set_def project_act_def)
apply (elim disjE bexE)
 apply (rule_tac x=Id in bexI)
  apply (blast intro!: rev_bexI )+
done

lemma project_unless2:
     "[| G ∈ stable C;  project h C G ∈ (project_set h C ∩ A) unless B |]
```

```
      ==> G ∈ (C ∩ extend_set h A) unless (extend_set h B)"
by (auto dest: stable_constrains_Int intro: constrains_weaken
         simp add: unless_def project_constrains Diff_eq Int_assoc
                   Int_extend_set_lemma)


lemma extend_unless:
   "[|extend h F ∈ stable C; F ∈ A unless B|]
    ==> extend h F ∈ C ∩ extend_set h A unless extend_set h B"
apply (simp add: unless_def stable_def)
apply (drule constrains_Int)
apply (erule extend_constrains [THEN iffD2])
apply (erule constrains_weaken, blast)
apply blast
done


lemma Join_project_ensures:
     "[| extend h F⊔G ∈ stable C;
         F⊔project h C G ∈ A ensures B |]
      ==> extend h F⊔G ∈ (C ∩ extend_set h A) ensures (extend_set h B)"
apply (auto simp add: ensures_eq extend_unless project_unless)
apply (blast intro:  extend_transient [THEN iffD2] transient_strengthen)
apply (blast intro: project_transient_extend_set transient_strengthen)
done
```

Lemma useful for both STRONG and WEAK progress, but the transient condition's very strong

```
lemma PLD_lemma:
     "[| extend h F⊔G ∈ stable C;
         F⊔project h C G ∈ (project_set h C ∩ A) leadsTo B |]
      ==> extend h F⊔G ∈
          C ∩ extend_set h (project_set h C ∩ A) leadsTo (extend_set h B)"
apply (erule leadsTo_induct)
  apply (blast intro: Join_project_ensures)
 apply (blast intro: psp_stable2 [THEN leadsTo_weaken_L] leadsTo_Trans)
apply (simp del: UN_simps add: Int_UN_distrib leadsTo_UN extend_set_Union)
done

lemma project_leadsTo_D_lemma:
     "[| extend h F⊔G ∈ stable C;
         F⊔project h C G ∈ (project_set h C ∩ A) leadsTo B |]
      ==> extend h F⊔G ∈ (C ∩ extend_set h A) leadsTo (extend_set h B)"
apply (rule PLD_lemma [THEN leadsTo_weaken])
apply (auto simp add: split_extended_all)
done

lemma Join_project_LeadsTo:
     "[| C = (reachable (extend h F⊔G));
         F⊔project h C G ∈ A LeadsTo B |]
      ==> extend h F⊔G ∈ (extend_set h A) LeadsTo (extend_set h B)"
by (simp del: Join_stable    add: LeadsTo_def project_leadsTo_D_lemma
                                  project_set_reachable_extend_eq)
```

27.7 Towards the theorem *project_Ensures_D*

lemma *project_ensures_D_lemma:*
```
     "[| G ∈ stable ((C ∩ extend_set h A) - (extend_set h B));
         F⊔project h C G ∈ (project_set h C ∩ A) ensures B;
         extend h F⊔G ∈ stable C |]
      ==> extend h F⊔G ∈ (C ∩ extend_set h A) ensures (extend_set h B)"

apply (auto intro!: project_unless2 [unfolded unless_def]
            intro: project_extend_constrains_I
            simp add: ensures_def)


 prefer 2
 apply (blast intro: project_transient_extend_set)

apply (force elim!: extend_transient [THEN iffD2, THEN transient_strengthen]
             simp add: split_extended_all)
done

lemma project_ensures_D:
     "[| F⊔project h UNIV G ∈ A ensures B;
         G ∈ stable (extend_set h A - extend_set h B) |]
      ==> extend h F⊔G ∈ (extend_set h A) ensures (extend_set h B)"
apply (rule project_ensures_D_lemma [of _ UNIV, elim_format], auto)
done

lemma project_Ensures_D:
     "[| F⊔project h (reachable (extend h F⊔G)) G ∈ A Ensures B;
         G ∈ stable (reachable (extend h F⊔G) ∩ extend_set h A -
                     extend_set h B) |]
      ==> extend h F⊔G ∈ (extend_set h A) Ensures (extend_set h B)"
apply (unfold Ensures_def)
apply (rule project_ensures_D_lemma [elim_format])
apply (auto simp add: project_set_reachable_extend_eq [symmetric])
done
```

27.8 Guarantees

lemma *project_act_Restrict_subset_project_act:*
```
     "project_act h (Restrict C act) ⊆ project_act h act"
apply (auto simp add: project_act_def)
done


lemma subset_closed_ok_extend_imp_ok_project:
     "[| extend h F ok G; subset_closed (AllowedActs F) |]
      ==> F ok project h C G"
apply (auto simp add: ok_def)
apply (rename_tac act)
apply (drule subsetD, blast)
apply (rule_tac x = "Restrict C  (extend_act h act)" in rev_image_eqI)
apply simp +
apply (cut_tac project_act_Restrict_subset_project_act)
apply (auto simp add: subset_closed_def)
```

done

lemma *project_guarantees_raw:*
assumes *xguary: "F ∈ X guarantees Y"*
and *closed: "subset_closed (AllowedActs F)"*
and *project: "!!G. extend h F⊔G ∈ X'*
==> F⊔project h (C G) G ∈ X"
and *extend: "!!G. [| F⊔project h (C G) G ∈ Y |]*
==> extend h F⊔G ∈ Y'"
shows *"extend h F ∈ X' guarantees Y'"*
apply *(rule xguary [THEN guaranteesD, THEN extend, THEN guaranteesI])*
apply *(blast intro: closed subset_closed_ok_extend_imp_ok_project)*
apply *(erule project)*
done

lemma *project_guarantees:*
"[| F ∈ X guarantees Y; subset_closed (AllowedActs F);
projecting C h F X' X; extending C h F Y' Y |]
==> extend h F ∈ X' guarantees Y'"
apply *(rule guaranteesI)*
apply *(auto simp add: guaranteesD projecting_def extending_def*
subset_closed_ok_extend_imp_ok_project)
done

27.9 guarantees corollaries

27.9.1 Some could be deleted: the required versions are easy to prove

lemma *extend_guar_increasing:*
"[| F ∈ UNIV guarantees increasing func;
subset_closed (AllowedActs F) |]
==> extend h F ∈ X' guarantees increasing (func o f)"
apply *(erule project_guarantees)*
apply *(rule_tac [3] extending_increasing)*
apply *(rule_tac [2] projecting_UNIV, auto)*
done

lemma *extend_guar_Increasing:*
"[| F ∈ UNIV guarantees Increasing func;
subset_closed (AllowedActs F) |]
==> extend h F ∈ X' guarantees Increasing (func o f)"
apply *(erule project_guarantees)*
apply *(rule_tac [3] extending_Increasing)*
apply *(rule_tac [2] projecting_UNIV, auto)*
done

lemma *extend_guar_Always:*
"[| F ∈ Always A guarantees Always B;
subset_closed (AllowedActs F) |]
==> extend h F

```
          ∈ Always(extend_set h A) guarantees Always(extend_set h B)"
apply (erule project_guarantees)
apply (rule_tac [3] extending_Always)
apply (rule_tac [2] projecting_Always, auto)
done
```

27.9.2 Guarantees with a leadsTo postcondition

```
lemma project_leadsTo_D:
     "F⊔project h UNIV G ∈ A leadsTo B
      ==> extend h F⊔G ∈ (extend_set h A) leadsTo (extend_set h B)"
apply (rule_tac C1 = UNIV in project_leadsTo_D_lemma [THEN leadsTo_weaken],
auto)
done

lemma project_LeadsTo_D:
     "F⊔project h (reachable (extend h F⊔G)) G ∈ A LeadsTo B
       ==> extend h F⊔G ∈ (extend_set h A) LeadsTo (extend_set h B)"
apply (rule refl [THEN Join_project_LeadsTo], auto)
done

lemma extending_leadsTo:
     "extending (%G. UNIV) h F
                (extend_set h A leadsTo extend_set h B) (A leadsTo B)"
apply (unfold extending_def)
apply (blast intro: project_leadsTo_D)
done

lemma extending_LeadsTo:
     "extending (%G. reachable (extend h F⊔G)) h F
                (extend_set h A LeadsTo extend_set h B) (A LeadsTo B)"
apply (unfold extending_def)
apply (blast intro: project_LeadsTo_D)
done

end

end
```

28 Progress Under Allowable Sets

```
theory ELT imports Project begin

inductive_set

  elt :: "['a set set, 'a program] => ('a set * 'a set) set"
  for CC :: "'a set set" and F :: "'a program"
 where

   Basis:  "[| F ∈ A ensures B;  A-B ∈ (insert {} CC) |] ==> (A,B) ∈ elt
CC F"

 | Trans:  "[| (A,B) ∈ elt CC F;  (B,C) ∈ elt CC F |] ==> (A,C) ∈ elt CC F"
```

```
 | Union:  "∀A∈S. (A,B) ∈ elt CC F ==> (Union S, B) ∈ elt CC F"
```

definition

```
  givenBy :: "['a => 'b] => 'a set set"
  where "givenBy f = range (%B. f-‘ B)"
```

definition

```
  leadsETo :: "['a set, 'a set set, 'a set] => 'a program set"
                                        ("(3_/ leadsTo[_]/ _)" [80,0,80] 80)
  where "leadsETo A CC B = {F. (A,B) ∈ elt CC F}"
```

definition

```
  LeadsETo :: "['a set, 'a set set, 'a set] => 'a program set"
                                        ("(3_/ LeadsTo[_]/ _)" [80,0,80] 80)
  where "LeadsETo A CC B =
      {F. F ∈ (reachable F Int A) leadsTo[(%C. reachable F Int C) ‘ CC] B}"
```

lemma *givenBy_id [simp]: "givenBy id = UNIV"*
by *(unfold givenBy_def, auto)*

lemma *givenBy_eq_all: "(givenBy v) = {A. ∀x∈A. ∀y. v x = v y ⟶ y ∈ A}"*
apply *(unfold givenBy_def, safe)*
apply *(rule_tac [2] x = "v ‘ _" in image_eqI, auto)*
done

lemma *givenByI: "(⋀x y. [| x ∈ A; v x = v y |] ==> y ∈ A) ==> A ∈ givenBy v"*
by *(subst givenBy_eq_all, blast)*

lemma *givenByD: "[| A ∈ givenBy v; x ∈ A; v x = v y |] ==> y ∈ A"*
by *(unfold givenBy_def, auto)*

lemma *empty_mem_givenBy [iff]: "{} ∈ givenBy v"*
by *(blast intro!: givenByI)*

lemma *givenBy_imp_eq_Collect: "A ∈ givenBy v ==> ∃P. A = {s. P(v s)}"*
apply *(rule_tac x = "λn. ∃s. v s = n ∧ s ∈ A" in exI)*
apply *(simp (no_asm_use) add: givenBy_eq_all)*
apply *blast*
done

lemma *Collect_mem_givenBy: "{s. P(v s)} ∈ givenBy v"*
by *(unfold givenBy_def, best)*

lemma *givenBy_eq_Collect: "givenBy v = {A. ∃P. A = {s. P(v s)}}"*
by *(blast intro: Collect_mem_givenBy givenBy_imp_eq_Collect)*

lemma *preserves_givenBy_imp_stable:*
"[| F ∈ preserves v; D ∈ givenBy v |] ==> F ∈ stable D"
by *(force simp add: preserves_subset_stable [THEN subsetD] givenBy_eq_Collect)*

lemma *givenBy_o_subset: "givenBy (w o v) <= givenBy v"*
apply *(simp (no_asm) add: givenBy_eq_Collect)*
apply *best*
done

lemma *givenBy_DiffI:*
"[| A ∈ givenBy v; B ∈ givenBy v |] ==> A-B ∈ givenBy v"
apply *(simp (no_asm_use) add: givenBy_eq_Collect)*
apply *safe*
apply *(rule_tac x = "%z. R z & ~ Q z"* **for** *R Q* **in** *exI)*
unfolding *set_diff_eq*
apply *auto*
done

lemma *leadsETo_Basis [intro]:*
"[| F ∈ A ensures B; A-B ∈ insert {} CC |] ==> F ∈ A leadsTo[CC] B"
apply *(unfold leadsETo_def)*
apply *(blast intro: elt.Basis)*
done

lemma *leadsETo_Trans:*
"[| F ∈ A leadsTo[CC] B; F ∈ B leadsTo[CC] C |] ==> F ∈ A leadsTo[CC] C"
apply *(unfold leadsETo_def)*
apply *(blast intro: elt.Trans)*
done

lemma *leadsETo_Un_duplicate:*
"F ∈ A leadsTo[CC] (A' ∪ A') ⟹ F ∈ A leadsTo[CC] A'"
by *(simp add: Un_ac)*

lemma *leadsETo_Un_duplicate2:*
"F ∈ A leadsTo[CC] (A' ∪ C ∪ C) ==> F ∈ A leadsTo[CC] (A' Un C)"
by *(simp add: Un_ac)*

lemma *leadsETo_Union:*
"(⋀A. A ∈ S ⟹ F ∈ A leadsTo[CC] B) ⟹ F ∈ (⋃S) leadsTo[CC] B"
apply *(unfold leadsETo_def)*
apply *(blast intro: elt.Union)*
done

lemma *leadsETo_UN:*
"(⋀i. i ∈ I ⟹ F ∈ (A i) leadsTo[CC] B)
==> F ∈ (UN i:I. A i) leadsTo[CC] B"

```
apply (blast intro: leadsETo_Union)
done


lemma leadsETo_induct:
  "[| F ∈ za leadsTo[CC] zb;
      !!A B. [| F ∈ A ensures B;  A-B ∈ insert {} CC |] ==> P A B;
      !!A B C. [| F ∈ A leadsTo[CC] B; P A B; F ∈ B leadsTo[CC] C; P B C
|]
               ==> P A C;
      !!B S. ∀A∈S. F ∈ A leadsTo[CC] B & P A B ==> P (⋃S) B
   |] ==> P za zb"
apply (unfold leadsETo_def)
apply (drule CollectD)
apply (erule elt.induct, blast+)
done



lemma leadsETo_mono: "CC' <= CC ==> (A leadsTo[CC'] B) <= (A leadsTo[CC]
B)"
apply safe
apply (erule leadsETo_induct)
prefer 3 apply (blast intro: leadsETo_Union)
prefer 2 apply (blast intro: leadsETo_Trans)
apply blast
done

lemma leadsETo_Trans_Un:
     "[| F ∈ A leadsTo[CC] B;  F ∈ B leadsTo[DD] C |]
      ==> F ∈ A leadsTo[CC Un DD] C"
by (blast intro: leadsETo_mono [THEN subsetD] leadsETo_Trans)

lemma leadsETo_Union_Int:
 "(!!A. A ∈ S ==> F ∈ (A Int C) leadsTo[CC] B)
  ==> F ∈ (⋃S Int C) leadsTo[CC] B"
apply (unfold leadsETo_def)
apply (simp only: Int_Union_Union)
apply (blast intro: elt.Union)
done


lemma leadsETo_Un:
     "[| F ∈ A leadsTo[CC] C; F ∈ B leadsTo[CC] C |]
      ==> F ∈ (A Un B) leadsTo[CC] C"
  using leadsETo_Union [of "{A, B}" F CC C] by auto

lemma single_leadsETo_I:
     "(⋀x. x ∈ A ==> F ∈ {x} leadsTo[CC] B) ⟹ F ∈ A leadsTo[CC] B"
by (subst UN_singleton [symmetric], rule leadsETo_UN, blast)


lemma subset_imp_leadsETo: "A<=B ⟹ F ∈ A leadsTo[CC] B"
```

by *(simp add: subset_imp_ensures [THEN leadsETo_Basis]*
Diff_eq_empty_iff [THEN iffD2])

lemmas *empty_leadsETo = empty_subsetI [THEN subset_imp_leadsETo, simp]*

lemma *leadsETo_weaken_R:*
"[| F ∈ A leadsTo[CC] A'; A'<=B' |] ==> F ∈ A leadsTo[CC] B'"
by *(blast intro: subset_imp_leadsETo leadsETo_Trans)*

lemma *leadsETo_weaken_L:*
"[| F ∈ A leadsTo[CC] A'; B<=A |] ==> F ∈ B leadsTo[CC] A'"
by *(blast intro: leadsETo_Trans subset_imp_leadsETo)*

lemma *leadsETo_Un_distrib:*
"F ∈ (A Un B) leadsTo[CC] C =
(F ∈ A leadsTo[CC] C ∧ F ∈ B leadsTo[CC] C)"
by *(blast intro: leadsETo_Un leadsETo_weaken_L)*

lemma *leadsETo_UN_distrib:*
"F ∈ (UN i:I. A i) leadsTo[CC] B =
(∀i∈I. F ∈ (A i) leadsTo[CC] B)"
by *(blast intro: leadsETo_UN leadsETo_weaken_L)*

lemma *leadsETo_Union_distrib:*
"F ∈ (⋃S) leadsTo[CC] B = (∀A∈S. F ∈ A leadsTo[CC] B)"
by *(blast intro: leadsETo_Union leadsETo_weaken_L)*

lemma *leadsETo_weaken:*
"[| F ∈ A leadsTo[CC'] A'; B<=A; A'<=B'; CC' <= CC |]
==> F ∈ B leadsTo[CC] B'"
apply *(drule leadsETo_mono [THEN subsetD], assumption)*
apply *(blast del: subsetCE*
intro: leadsETo_weaken_R leadsETo_weaken_L leadsETo_Trans)
done

lemma *leadsETo_givenBy:*
"[| F ∈ A leadsTo[CC] A'; CC <= givenBy v |]
==> F ∈ A leadsTo[givenBy v] A'"
by *(blast intro: leadsETo_weaken)*

lemma *leadsETo_Diff:*
"[| F ∈ (A-B) leadsTo[CC] C; F ∈ B leadsTo[CC] C |]
==> F ∈ A leadsTo[CC] C"
by *(blast intro: leadsETo_Un leadsETo_weaken)*

```
lemma leadsETo_Un_Un:
     "[| F ∈ A leadsTo[CC] A';  F ∈ B leadsTo[CC] B' |]
      ==> F ∈ (A Un B) leadsTo[CC] (A' Un B')"
by (blast intro: leadsETo_Un leadsETo_weaken_R)



lemma leadsETo_cancel2:
     "[| F ∈ A leadsTo[CC] (A' Un B); F ∈ B leadsTo[CC] B' |]
      ==> F ∈ A leadsTo[CC] (A' Un B')"
by (blast intro: leadsETo_Un_Un subset_imp_leadsETo leadsETo_Trans)

lemma leadsETo_cancel1:
     "[| F ∈ A leadsTo[CC] (B Un A'); F ∈ B leadsTo[CC] B' |]
    ==> F ∈ A leadsTo[CC] (B' Un A')"
apply (simp add: Un_commute)
apply (blast intro!: leadsETo_cancel2)
done

lemma leadsETo_cancel_Diff1:
     "[| F ∈ A leadsTo[CC] (B Un A'); F ∈ (B-A') leadsTo[CC] B' |]
    ==> F ∈ A leadsTo[CC] (B' Un A')"
apply (rule leadsETo_cancel1)
 prefer 2 apply assumption
apply simp_all
done



lemma e_psp_stable:
   "[| F ∈ A leadsTo[CC] A';  F ∈ stable B;  ∀C∈CC. C Int B ∈ CC |]
    ==> F ∈ (A Int B) leadsTo[CC] (A' Int B)"
apply (unfold stable_def)
apply (erule leadsETo_induct)
prefer 3 apply (blast intro: leadsETo_Union_Int)
prefer 2 apply (blast intro: leadsETo_Trans)
apply (rule leadsETo_Basis)
prefer 2 apply (force simp add: Diff_Int_distrib2 [symmetric])
apply (simp add: ensures_def Diff_Int_distrib2 [symmetric]
                 Int_Un_distrib2 [symmetric])
apply (blast intro: transient_strengthen constrains_Int)
done

lemma e_psp_stable2:
     "[| F ∈ A leadsTo[CC] A'; F ∈ stable B;  ∀C∈CC. C Int B ∈ CC |]
      ==> F ∈ (B Int A) leadsTo[CC] (B Int A')"
by (simp (no_asm_simp) add: e_psp_stable Int_ac)

lemma e_psp:
     "[| F ∈ A leadsTo[CC] A'; F ∈ B co B';
         ∀C∈CC. C Int B Int B' ∈ CC |]
```

```
      ==> F ∈ (A Int B') leadsTo[CC] ((A' Int B) Un (B' - B))"
apply (erule leadsETo_induct)
prefer 3 apply (blast intro: leadsETo_Union_Int)

apply (rule_tac [2] leadsETo_Un_duplicate2)
apply (erule_tac [2] leadsETo_cancel_Diff1)
prefer 2
 apply (simp add: Int_Diff Diff_triv)
 apply (blast intro: leadsETo_weaken_L dest: constrains_imp_subset)

apply (rule leadsETo_Basis)
apply (blast intro: psp_ensures)
apply (subgoal_tac "A Int B' - (Ba Int B Un (B' - B)) = (A - Ba) Int B Int
B'")
apply auto
done

lemma e_psp2:
     "[| F ∈ A leadsTo[CC] A'; F ∈ B co B';
         ∀C∈CC. C Int B Int B' ∈ CC |]
      ==> F ∈ (B' Int A) leadsTo[CC] ((B Int A') Un (B' - B))"
by (simp add: e_psp Int_ac)




lemma gen_leadsETo_imp_Join_leadsETo:
     "[| F ∈ (A leadsTo[givenBy v] B);  G ∈ preserves v;
         F⊔G ∈ stable C |]
      ==> F⊔G ∈ ((C Int A) leadsTo[(%D. C Int D) ` givenBy v] B)"
apply (erule leadsETo_induct)
  prefer 3
  apply (subst Int_Union)
  apply (blast intro: leadsETo_UN)
prefer 2
 apply (blast intro: e_psp_stable2 [THEN leadsETo_weaken_L] leadsETo_Trans)
apply (rule leadsETo_Basis)
apply (auto simp add: Diff_eq_empty_iff [THEN iffD2]
                      Int_Diff ensures_def givenBy_eq_Collect)
prefer 3 apply (blast intro: transient_strengthen)
apply (drule_tac [2] P1 = P in preserves_subset_stable [THEN subsetD])
apply (drule_tac P1 = P in preserves_subset_stable [THEN subsetD])
apply (unfold stable_def)
apply (blast intro: constrains_Int [THEN constrains_weaken])+
done




lemma leadsETo_subset_leadsTo: "(A leadsTo[CC] B) <= (A leadsTo B)"
apply safe
apply (erule leadsETo_induct)
```

```
  prefer 3 apply (blast intro: leadsTo_Union)
 prefer 2 apply (blast intro: leadsTo_Trans, blast)
done

lemma leadsETo_UNIV_eq_leadsTo: "(A leadsTo[UNIV] B) = (A leadsTo B)"
apply safe
apply (erule leadsETo_subset_leadsTo [THEN subsetD])

apply (erule leadsTo_induct)
  prefer 3 apply (blast intro: leadsETo_Union)
 prefer 2 apply (blast intro: leadsETo_Trans, blast)
done



lemma LeadsETo_eq_leadsETo:
     "A LeadsTo[CC] B =
        {F. F ∈ (reachable F Int A) leadsTo[(%C. reachable F Int C) ‘ CC]

        (reachable F Int B)}"
apply (unfold LeadsETo_def)
apply (blast dest: e_psp_stable2 intro: leadsETo_weaken)
done



lemma LeadsETo_Trans:
     "[| F ∈ A LeadsTo[CC] B;  F ∈ B LeadsTo[CC] C |]
      ==> F ∈ A LeadsTo[CC] C"
apply (simp add: LeadsETo_eq_leadsETo)
apply (blast intro: leadsETo_Trans)
done

lemma LeadsETo_Union:
     "(⋀A. A ∈ S ⟹ F ∈ A LeadsTo[CC] B) ⟹ F ∈ (⋃S) LeadsTo[CC] B"
apply (simp add: LeadsETo_def)
apply (subst Int_Union)
apply (blast intro: leadsETo_UN)
done

lemma LeadsETo_UN:
     "(⋀i. i ∈ I ⟹ F ∈ (A i) LeadsTo[CC] B)
      ⟹ F ∈ (UN i:I. A i) LeadsTo[CC] B"
apply (blast intro: LeadsETo_Union)
done


lemma LeadsETo_Un:
     "[| F ∈ A LeadsTo[CC] C; F ∈ B LeadsTo[CC] C |]
      ==> F ∈ (A Un B) LeadsTo[CC] C"
  using LeadsETo_Union [of "{A, B}" F CC C] by auto


lemma single_LeadsETo_I:
```

```
    "(⋀s. s ∈ A ==> F ∈ {s} LeadsTo[CC] B) ⟹ F ∈ A LeadsTo[CC] B"
by (subst UN_singleton [symmetric], rule LeadsETo_UN, blast)

lemma subset_imp_LeadsETo:
    "A <= B ⟹ F ∈ A LeadsTo[CC] B"
apply (simp (no_asm) add: LeadsETo_def)
apply (blast intro: subset_imp_leadsETo)
done

lemmas empty_LeadsETo = empty_subsetI [THEN subset_imp_LeadsETo]

lemma LeadsETo_weaken_R:
    "[| F ∈ A LeadsTo[CC] A';  A' <= B' |] ==> F ∈ A LeadsTo[CC] B'"
apply (simp add: LeadsETo_def)
apply (blast intro: leadsETo_weaken_R)
done

lemma LeadsETo_weaken_L:
    "[| F ∈ A LeadsTo[CC] A';  B <= A |] ==> F ∈ B LeadsTo[CC] A'"
apply (simp add: LeadsETo_def)
apply (blast intro: leadsETo_weaken_L)
done

lemma LeadsETo_weaken:
    "[| F ∈ A LeadsTo[CC'] A';
        B <= A;  A' <= B';  CC' <= CC |]
     ==> F ∈ B LeadsTo[CC] B'"
apply (simp (no_asm_use) add: LeadsETo_def)
apply (blast intro: leadsETo_weaken)
done

lemma LeadsETo_subset_LeadsTo: "(A LeadsTo[CC] B) <= (A LeadsTo B)"
apply (unfold LeadsETo_def LeadsTo_def)
apply (blast intro: leadsETo_subset_leadsTo [THEN subsetD])
done


lemma reachable_ensures:
    "F ∈ A ensures B ⟹ F ∈ (reachable F Int A) ensures B"
apply (rule stable_ensures_Int [THEN ensures_weaken_R], auto)
done

lemma lel_lemma:
    "F ∈ A leadsTo B ⟹ F ∈ (reachable F Int A) leadsTo[Pow(reachable F)]
B"
apply (erule leadsTo_induct)
  apply (blast intro: reachable_ensures)
 apply (blast dest: e_psp_stable2 intro: leadsETo_Trans leadsETo_weaken_L)
apply (subst Int_Union)
apply (blast intro: leadsETo_UN)
done

lemma LeadsETo_UNIV_eq_LeadsTo: "(A LeadsTo[UNIV] B) = (A LeadsTo B)"
apply safe
```

```
apply (erule LeadsETo_subset_LeadsTo [THEN subsetD])

apply (unfold LeadsETo_def LeadsTo_def)
apply (blast intro: lel_lemma [THEN leadsETo_weaken])
done



context Extend
begin

lemma givenBy_o_eq_extend_set:
     "givenBy (v o f) = extend_set h ` (givenBy v)"
apply (simp add: givenBy_eq_Collect)
apply (rule equalityI, best)
apply blast
done

lemma givenBy_eq_extend_set: "givenBy f = range (extend_set h)"
by (simp add: givenBy_eq_Collect, best)

lemma extend_set_givenBy_I:
     "D ∈ givenBy v ==> extend_set h D ∈ givenBy (v o f)"
apply (simp (no_asm_use) add: givenBy_eq_all, blast)
done

lemma leadsETo_imp_extend_leadsETo:
     "F ∈ A leadsTo[CC] B
      ==> extend h F ∈ (extend_set h A) leadsTo[extend_set h ` CC]
                       (extend_set h B)"
apply (erule leadsETo_induct)
  apply (force intro: subset_imp_ensures
               simp add: extend_ensures extend_set_Diff_distrib [symmetric])
 apply (blast intro: leadsETo_Trans)
apply (simp add: leadsETo_UN extend_set_Union)
done



lemma Join_project_ensures_strong:
     "[| project h C G ∉ transient (project_set h C Int (A-B)) |
           project_set h C Int (A - B) = {};
         extend h F⊔G ∈ stable C;
         F⊔project h C G ∈ (project_set h C Int A) ensures B |]
      ==> extend h F⊔G ∈ (C Int extend_set h A) ensures (extend_set h B)"
apply (subst Int_extend_set_lemma [symmetric])
apply (rule Join_project_ensures)
apply (auto simp add: Int_Diff)
done
```

```
lemma pli_lemma:
     "[| extend h F⊔G ∈ stable C;
         F⊔project h C G
           ∈ project_set h C Int project_set h A leadsTo project_set h B |]

      ==> F⊔project h C G
            ∈ project_set h C Int project_set h A leadsTo
              project_set h C Int project_set h B"
apply (rule psp_stable2 [THEN leadsTo_weaken_L])
apply (auto simp add: project_stable_project_set extend_stable_project_set)
done

lemma project_leadsETo_I_lemma:
     "[| extend h F⊔G ∈ stable C;
         extend h F⊔G ∈
           (C Int A) leadsTo[(%D. C Int D)`givenBy f]  B |]
  ==> F⊔project h C G
    ∈ (project_set h C Int project_set h (C Int A)) leadsTo (project_set h
B)"
apply (erule leadsETo_induct)
  prefer 3
  apply (simp only: Int_UN_distrib project_set_Union)
  apply (blast intro: leadsTo_UN)
 prefer 2 apply (blast intro: leadsTo_Trans pli_lemma)
apply (simp add: givenBy_eq_extend_set)
apply (rule leadsTo_Basis)
apply (blast intro: ensures_extend_set_imp_project_ensures)
done

lemma project_leadsETo_I:
     "extend h F⊔G ∈ (extend_set h A) leadsTo[givenBy f] (extend_set h B)
      ⟹ F⊔project h UNIV G ∈ A leadsTo B"
apply (rule project_leadsETo_I_lemma [THEN leadsTo_weaken], auto)
done

lemma project_LeadsETo_I:
     "extend h F⊔G ∈ (extend_set h A) LeadsTo[givenBy f] (extend_set h B)

      ⟹ F⊔project h (reachable (extend h F⊔G)) G
           ∈ A LeadsTo B"
apply (simp (no_asm_use) add: LeadsTo_def LeadsETo_def)
apply (rule project_leadsETo_I_lemma [THEN leadsTo_weaken])
apply (auto simp add: project_set_reachable_extend_eq [symmetric])
done

lemma projecting_leadsTo:
     "projecting (λG. UNIV) h F
                 (extend_set h A leadsTo[givenBy f] extend_set h B)
                 (A leadsTo B)"
apply (unfold projecting_def)
apply (force dest: project_leadsETo_I)
```

done

lemma *projecting_LeadsTo:*
```
     "projecting (λG. reachable (extend h F⊔G)) h F
                 (extend_set h A LeadsTo[givenBy f] extend_set h B)
                 (A LeadsTo B)"
```
apply *(unfold projecting_def)*
apply *(force dest: project_LeadsETo_I)*
done

end

end