

Hoare Logic for Parallel Programs

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Abstract

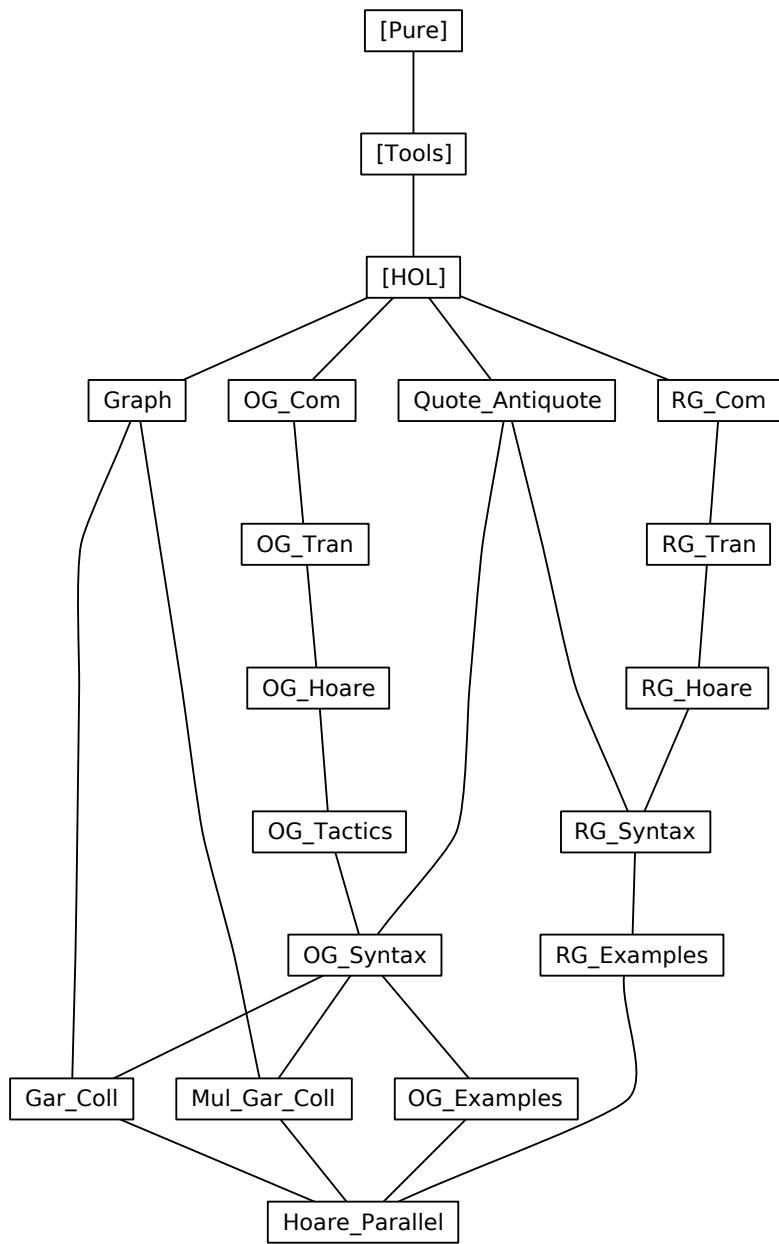
In the following theories a formalization of the Owicki-Gries and the rely-guarantee methods is presented. These methods are widely used for correctness proofs of parallel imperative programs with shared variables. We define syntax, semantics and proof rules in Isabelle/HOL. The proof rules also provide for programs parameterized in the number of parallel components. Their correctness w.r.t. the semantics is proven. Completeness proofs for both methods are extended to the new case of parameterized programs. (These proofs have not been formalized in Isabelle. They can be found in [1].) Using this formalizations we verify several non-trivial examples for parameterized and non-parameterized programs. For the automatic generation of verification conditions with the Owicki-Gries method we define a tactic based on the proof rules. The most involved examples are the verification of two garbage-collection algorithms, the second one parameterized in the number of mutators.

For excellent descriptions of this work see [2, 4, 1, 3].

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Chapter 1

The Owicki-Gries Method

1.1 Abstract Syntax

theory *OG-Com* **imports** *Main* **begin**

Type abbreviations for boolean expressions and assertions:

type-synonym *'a bexp* = *'a set*

type-synonym *'a assn* = *'a set*

The syntax of commands is defined by two mutually recursive datatypes: *'a ann-com* for annotated commands and *'a com* for non-annotated commands.

datatype *'a ann-com* =
 AnnBasic (*'a assn*) (*'a \Rightarrow 'a*)
 | *AnnSeq* (*'a ann-com*) (*'a ann-com*)
 | *AnnCond1* (*'a assn*) (*'a bexp*) (*'a ann-com*) (*'a ann-com*)
 | *AnnCond2* (*'a assn*) (*'a bexp*) (*'a ann-com*)
 | *AnnWhile* (*'a assn*) (*'a bexp*) (*'a assn*) (*'a ann-com*)
 | *AnnAwait* (*'a assn*) (*'a bexp*) (*'a com*)
and *'a com* =
 Parallel (*'a ann-com option* \times *'a assn*) *list*
 | *Basic* (*'a \Rightarrow 'a*)
 | *Seq* (*'a com*) (*'a com*)
 | *Cond* (*'a bexp*) (*'a com*) (*'a com*)
 | *While* (*'a bexp*) (*'a assn*) (*'a com*)

The function *pre* extracts the precondition of an annotated command:

primrec *pre* :: *'a ann-com \Rightarrow 'a assn* **where**
 pre (*AnnBasic* *r f*) = *r*
 | *pre* (*AnnSeq* *c1 c2*) = *pre c1*
 | *pre* (*AnnCond1* *r b c1 c2*) = *r*
 | *pre* (*AnnCond2* *r b c*) = *r*
 | *pre* (*AnnWhile* *r b i c*) = *r*
 | *pre* (*AnnAwait* *r b c*) = *r*

Well-formedness predicate for atomic programs:

primrec *atom-com* :: 'a com \Rightarrow bool **where**
 | *atom-com* (Parallel Ts) = False
 | *atom-com* (Basic f) = True
 | *atom-com* (Seq c1 c2) = (*atom-com* c1 \wedge *atom-com* c2)
 | *atom-com* (Cond b c1 c2) = (*atom-com* c1 \wedge *atom-com* c2)
 | *atom-com* (While b i c) = *atom-com* c

end

1.2 Operational Semantics

theory *OG-Tran* **imports** *OG-Com* **begin**

type-synonym 'a ann-com-op = ('a ann-com) option
type-synonym 'a ann-triple-op = ('a ann-com-op \times 'a assn)

primrec *com* :: 'a ann-triple-op \Rightarrow 'a ann-com-op **where**
com (c, q) = c

primrec *post* :: 'a ann-triple-op \Rightarrow 'a assn **where**
post (c, q) = q

definition *All-None* :: 'a ann-triple-op list \Rightarrow bool **where**
All-None Ts $\equiv \forall (c, q) \in \text{set } Ts. c = \text{None}$

1.2.1 The Transition Relation

inductive-set

ann-transition :: (('a ann-com-op \times 'a) \times ('a ann-com-op \times 'a)) set
and *transition* :: (('a com \times 'a) \times ('a com \times 'a)) set
and *ann-transition'* :: ('a ann-com-op \times 'a) \Rightarrow ('a ann-com-op \times 'a) \Rightarrow bool
 ($\langle \cdot \rangle -1 \rightarrow \rightarrow$ [81,81] 100)
and *transition'* :: ('a com \times 'a) \Rightarrow ('a com \times 'a) \Rightarrow bool
 ($\langle \cdot \rangle -P1 \rightarrow \rightarrow$ [81,81] 100)
and *transitions* :: ('a com \times 'a) \Rightarrow ('a com \times 'a) \Rightarrow bool
 ($\langle \cdot \rangle -P* \rightarrow \rightarrow$ [81,81] 100)

where

con-0 $-1 \rightarrow$ *con-1* $\equiv (con-0, con-1) \in \text{ann-transition}$
 | *con-0* $-P1 \rightarrow$ *con-1* $\equiv (con-0, con-1) \in \text{transition}$
 | *con-0* $-P* \rightarrow$ *con-1* $\equiv (con-0, con-1) \in \text{transition}^*$
 | *AnnBasic*: (Some (AnnBasic r f), s) $-1 \rightarrow$ (None, f s)
 | *AnnSeq1*: (Some c0, s) $-1 \rightarrow$ (None, t) \implies
 (Some (AnnSeq c0 c1), s) $-1 \rightarrow$ (Some c1, t)
 | *AnnSeq2*: (Some c0, s) $-1 \rightarrow$ (Some c2, t) \implies
 (Some (AnnSeq c0 c1), s) $-1 \rightarrow$ (Some (AnnSeq c2 c1), t)
 | *AnnCond1T*: s $\in b \implies$ (Some (AnnCond1 r b c1 c2), s) $-1 \rightarrow$ (Some c1, s)

| *AnnCond1F*: $s \notin b \implies (\text{Some } (\text{AnnCond1 } r \ b \ c1 \ c2), s) -1 \rightarrow (\text{Some } c2, s)$

| *AnnCond2T*: $s \in b \implies (\text{Some } (\text{AnnCond2 } r \ b \ c), s) -1 \rightarrow (\text{Some } c, s)$

| *AnnCond2F*: $s \notin b \implies (\text{Some } (\text{AnnCond2 } r \ b \ c), s) -1 \rightarrow (\text{None}, s)$

| *AnnWhileF*: $s \notin b \implies (\text{Some } (\text{AnnWhile } r \ b \ i \ c), s) -1 \rightarrow (\text{None}, s)$

| *AnnWhileT*: $s \in b \implies (\text{Some } (\text{AnnWhile } r \ b \ i \ c), s) -1 \rightarrow$
 $(\text{Some } (\text{AnnSeq } c \ (\text{AnnWhile } i \ b \ i \ c)), s)$

| *AnnAwait*: $\llbracket s \in b; \text{atom-com } c; (c, s) -P^* \rightarrow (\text{Parallel } [], t) \rrbracket \implies$
 $(\text{Some } (\text{AnnAwait } r \ b \ c), s) -1 \rightarrow (\text{None}, t)$

| *Parallel*: $\llbracket i < \text{length } Ts; Ts!i = (\text{Some } c, q); (\text{Some } c, s) -1 \rightarrow (r, t) \rrbracket$
 $\implies (\text{Parallel } Ts, s) -P1 \rightarrow (\text{Parallel } (Ts [i:= (r, q)]), t)$

| *Basic*: $(\text{Basic } f, s) -P1 \rightarrow (\text{Parallel } [], f \ s)$

| *Seq1*: $\text{All-None } Ts \implies (\text{Seq } (\text{Parallel } Ts) \ c, s) -P1 \rightarrow (c, s)$

| *Seq2*: $(c0, s) -P1 \rightarrow (c2, t) \implies (\text{Seq } c0 \ c1, s) -P1 \rightarrow (\text{Seq } c2 \ c1, t)$

| *CondT*: $s \in b \implies (\text{Cond } b \ c1 \ c2, s) -P1 \rightarrow (c1, s)$

| *CondF*: $s \notin b \implies (\text{Cond } b \ c1 \ c2, s) -P1 \rightarrow (c2, s)$

| *WhileF*: $s \notin b \implies (\text{While } b \ i \ c, s) -P1 \rightarrow (\text{Parallel } [], s)$

| *WhileT*: $s \in b \implies (\text{While } b \ i \ c, s) -P1 \rightarrow (\text{Seq } c \ (\text{While } b \ i \ c), s)$

monos *rtrancl-mono*

The corresponding abbreviations are:

abbreviation

ann-transition-n :: $('a \ \text{ann-com-op} \times 'a) \Rightarrow \text{nat} \Rightarrow ('a \ \text{ann-com-op} \times 'a)$
 $\Rightarrow \text{bool } (\leftarrow \dashrightarrow \rightarrow [81,81] \ 100) \ \mathbf{where}$
con-0 $-n \rightarrow$ *con-1* $\equiv (\text{con-0}, \text{con-1}) \in \text{ann-transition} \overset{\sim}{\sim} n$

abbreviation

ann-transitions :: $('a \ \text{ann-com-op} \times 'a) \Rightarrow ('a \ \text{ann-com-op} \times 'a) \Rightarrow \text{bool}$
 $(\leftarrow \dashrightarrow \rightarrow [81,81] \ 100) \ \mathbf{where}$
con-0 $-* \rightarrow$ *con-1* $\equiv (\text{con-0}, \text{con-1}) \in \text{ann-transition}^*$

abbreviation

transition-n :: $('a \ \text{com} \times 'a) \Rightarrow \text{nat} \Rightarrow ('a \ \text{com} \times 'a) \Rightarrow \text{bool}$
 $(\leftarrow -P \rightarrow \rightarrow [81,81,81] \ 100) \ \mathbf{where}$
con-0 $-Pn \rightarrow$ *con-1* $\equiv (\text{con-0}, \text{con-1}) \in \text{transition} \overset{\sim}{\sim} n$

1.2.2 Definition of Semantics

definition *ann-sem* :: $'a \ \text{ann-com} \Rightarrow 'a \Rightarrow 'a \ \text{set} \ \mathbf{where}$

ann-sem $c \equiv \lambda s. \{t. (\text{Some } c, s) -* \rightarrow (\text{None}, t)\}$

definition *ann-SEM* :: 'a *ann-com* \Rightarrow 'a *set* \Rightarrow 'a *set* **where**
ann-SEM *c S* $\equiv \bigcup (\text{ann-sem } c \text{ ' } S)$

definition *sem* :: 'a *com* \Rightarrow 'a \Rightarrow 'a *set* **where**
sem *c* $\equiv \lambda s. \{t. \exists Ts. (c, s) -P^* \rightarrow (\text{Parallel } Ts, t) \wedge \text{All-None } Ts\}$

definition *SEM* :: 'a *com* \Rightarrow 'a *set* \Rightarrow 'a *set* **where**
SEM *c S* $\equiv \bigcup (\text{sem } c \text{ ' } S)$

abbreviation *Omega* :: 'a *com* $\langle \Omega \rangle$ 63
where $\Omega \equiv \text{While UNIV UNIV (Basic id)}$

primrec *fwhile* :: 'a *bepr* \Rightarrow 'a *com* \Rightarrow *nat* \Rightarrow 'a *com* **where**
fwhile *b c 0* = Ω
 $| \text{fwhile } b \ c \ (Suc \ n) = \text{Cond } b \ (\text{Seq } c \ (\text{fwhile } b \ c \ n)) \ (\text{Basic id})$

Proofs

declare *ann-transition-transition.intros* [intro]

inductive-cases *transition-cases*:

- (*Parallel T, s*) -*P1* \rightarrow *t*
- (*Basic f, s*) -*P1* \rightarrow *t*
- (*Seq c1 c2, s*) -*P1* \rightarrow *t*
- (*Cond b c1 c2, s*) -*P1* \rightarrow *t*
- (*While b i c, s*) -*P1* \rightarrow *t*

lemma *Parallel-empty-lemma* [rule-format (no-asm)]:
(*Parallel [] , s*) -*Pn* \rightarrow (*Parallel Ts, t*) \longrightarrow $Ts = [] \wedge n = 0 \wedge s = t$
<proof>

lemma *Parallel-AllNone-lemma* [rule-format (no-asm)]:
All-None Ss \longrightarrow (*Parallel Ss, s*) -*Pn* \rightarrow (*Parallel Ts, t*) \longrightarrow $Ts = Ss \wedge n = 0 \wedge s = t$
<proof>

lemma *Parallel-AllNone*: *All-None Ts* \Longrightarrow (*SEM (Parallel Ts) X*) = *X*
<proof>

lemma *Parallel-empty*: $Ts = [] \Longrightarrow$ (*SEM (Parallel Ts) X*) = *X*
<proof>

Set of lemmas from Apt and Olderog "Verification of sequential and concurrent programs", page 63.

lemma *L3-5i*: $X \subseteq Y \Longrightarrow \text{SEM } c \ X \subseteq \text{SEM } c \ Y$
<proof>

lemma *L3-5ii-lemma1*:
 $\llbracket (c1, s1) -P^* \rightarrow (\text{Parallel } Ts, s2); \text{All-None } Ts;$
 $(c2, s2) -P^* \rightarrow (\text{Parallel } Ss, s3); \text{All-None } Ss \rrbracket$
 $\Longrightarrow (\text{Seq } c1 \ c2, s1) -P^* \rightarrow (\text{Parallel } Ss, s3)$

$\langle proof \rangle$

lemma *L3-5ii-lemma2* [rule-format (no-asm)]:

$\forall c1\ c2\ s\ t. (Seq\ c1\ c2, s) -Pn \rightarrow (Parallel\ Ts, t) \rightarrow$
 $(All\ None\ Ts) \rightarrow (\exists y\ m\ Rs. (c1, s) -P* \rightarrow (Parallel\ Rs, y) \wedge$
 $(All\ None\ Rs) \wedge (c2, y) -Pm \rightarrow (Parallel\ Ts, t) \wedge m \leq n)$
 $\langle proof \rangle$

lemma *L3-5ii-lemma3*:

$\llbracket (Seq\ c1\ c2, s) -P* \rightarrow (Parallel\ Ts, t); All\ None\ Ts \rrbracket \implies$
 $(\exists y\ Rs. (c1, s) -P* \rightarrow (Parallel\ Rs, y) \wedge All\ None\ Rs$
 $\wedge (c2, y) -P* \rightarrow (Parallel\ Ts, t))$
 $\langle proof \rangle$

lemma *L3-5ii*: $SEM\ (Seq\ c1\ c2)\ X = SEM\ c2\ (SEM\ c1\ X)$

$\langle proof \rangle$

lemma *L3-5iii*: $SEM\ (Seq\ (Seq\ c1\ c2)\ c3)\ X = SEM\ (Seq\ c1\ (Seq\ c2\ c3))\ X$

$\langle proof \rangle$

lemma *L3-5iv*:

$SEM\ (Cond\ b\ c1\ c2)\ X = (SEM\ c1\ (X \cap b))\ Un\ (SEM\ c2\ (X \cap (-b)))$
 $\langle proof \rangle$

lemma *L3-5v-lemma1* [rule-format]:

$(S, s) -Pn \rightarrow (T, t) \rightarrow S = \Omega \rightarrow (\neg(\exists Rs. T = (Parallel\ Rs) \wedge All\ None\ Rs))$
 $\langle proof \rangle$

lemma *L3-5v-lemma2*: $\llbracket (\Omega, s) -P* \rightarrow (Parallel\ Ts, t); All\ None\ Ts \rrbracket \implies False$

$\langle proof \rangle$

lemma *L3-5v-lemma3*: $SEM\ (\Omega)\ S = \{\}$

$\langle proof \rangle$

lemma *L3-5v-lemma4* [rule-format]:

$\forall s. (While\ b\ i\ c, s) -Pn \rightarrow (Parallel\ Ts, t) \rightarrow All\ None\ Ts \rightarrow$
 $(\exists k. (fwhile\ b\ c\ k, s) -P* \rightarrow (Parallel\ Ts, t))$
 $\langle proof \rangle$

lemma *L3-5v-lemma5* [rule-format]:

$\forall s. (fwhile\ b\ c\ k, s) -P* \rightarrow (Parallel\ Ts, t) \rightarrow All\ None\ Ts \rightarrow$
 $(While\ b\ i\ c, s) -P* \rightarrow (Parallel\ Ts, t)$
 $\langle proof \rangle$

lemma *L3-5v*: $SEM\ (While\ b\ i\ c) = (\lambda x. (\bigcup k. SEM\ (fwhile\ b\ c\ k)\ x))$

$\langle proof \rangle$

1.3 Validity of Correctness Formulas

definition *com-validity* :: 'a *assn* \Rightarrow 'a *com* \Rightarrow 'a *assn* \Rightarrow bool ($\langle \mathcal{S} \models - // - // - \rangle$)
 [90,55,90] 50) **where**
 $\models p \ c \ q \equiv SEM \ c \ p \subseteq q$

definition *ann-com-validity* :: 'a *ann-com* \Rightarrow 'a *assn* \Rightarrow bool ($\langle \models - \rightarrow [60,90] \ 45 \rangle$)
where
 $\models c \ q \equiv ann-SEM \ c \ (pre \ c) \subseteq q$

end

1.4 The Proof System

theory *OG-Hoare* **imports** *OG-Tran* **begin**

primrec *assertions* :: 'a *ann-com* \Rightarrow ('a *assn*) **set where**
 $assertions \ (AnnBasic \ r \ f) = \{r\}$
 $| \ assertions \ (AnnSeq \ c1 \ c2) = assertions \ c1 \cup assertions \ c2$
 $| \ assertions \ (AnnCond1 \ r \ b \ c1 \ c2) = \{r\} \cup assertions \ c1 \cup assertions \ c2$
 $| \ assertions \ (AnnCond2 \ r \ b \ c) = \{r\} \cup assertions \ c$
 $| \ assertions \ (AnnWhile \ r \ b \ i \ c) = \{r, i\} \cup assertions \ c$
 $| \ assertions \ (AnnAwait \ r \ b \ c) = \{r\}$

primrec *atomics* :: 'a *ann-com* \Rightarrow ('a *assn* \times 'a *com*) **set where**
 $atomics \ (AnnBasic \ r \ f) = \{(r, \ Basic \ f)\}$
 $| \ atomics \ (AnnSeq \ c1 \ c2) = atomics \ c1 \cup atomics \ c2$
 $| \ atomics \ (AnnCond1 \ r \ b \ c1 \ c2) = atomics \ c1 \cup atomics \ c2$
 $| \ atomics \ (AnnCond2 \ r \ b \ c) = atomics \ c$
 $| \ atomics \ (AnnWhile \ r \ b \ i \ c) = atomics \ c$
 $| \ atomics \ (AnnAwait \ r \ b \ c) = \{(r \cap b, \ c)\}$

primrec *com* :: 'a *ann-triple-op* \Rightarrow 'a *ann-com-op* **where**
 $com \ (c, \ q) = c$

primrec *post* :: 'a *ann-triple-op* \Rightarrow 'a *assn* **where**
 $post \ (c, \ q) = q$

definition *interfree-aux* :: ('a *ann-com-op* \times 'a *assn* \times 'a *ann-com-op*) \Rightarrow bool
where
 $interfree-aux \equiv \lambda(co, \ q, \ co'). \ co' = None \vee$
 $(\forall (r, a) \in atomics \ (the \ co'). \ \models (q \cap r) \ a \ q \wedge$
 $(co = None \vee (\forall p \in assertions \ (the \ co'). \ \models (p \cap r) \ a \ p)))$

definition *interfree* :: (('a *ann-triple-op*) *list*) \Rightarrow bool **where**
 $interfree \ Ts \equiv \forall i \ j. \ i < length \ Ts \wedge j < length \ Ts \wedge i \neq j \longrightarrow$
 $interfree-aux \ (com \ (Ts!i), \ post \ (Ts!i), \ com \ (Ts!j))$

inductive

oghoare :: 'a assn ⇒ 'a com ⇒ 'a assn ⇒ bool (⟨(3||- -//-/-)⟩ [90,55,90] 50)
and *ann-hoare* :: 'a ann-com ⇒ 'a assn ⇒ bool (⟨(2⊢ -//-)⟩ [60,90] 45)

where

AnnBasic: $r \subseteq \{s. f s \in q\} \implies \vdash (\text{AnnBasic } r f) q$

| *AnnSeq*: $\llbracket \vdash c0 \text{ pre } c1; \vdash c1 q \rrbracket \implies \vdash (\text{AnnSeq } c0 c1) q$

| *AnnCond1*: $\llbracket r \cap b \subseteq \text{pre } c1; \vdash c1 q; r \cap \neg b \subseteq \text{pre } c2; \vdash c2 q \rrbracket$
 $\implies \vdash (\text{AnnCond1 } r b c1 c2) q$

| *AnnCond2*: $\llbracket r \cap b \subseteq \text{pre } c; \vdash c q; r \cap \neg b \subseteq q \rrbracket \implies \vdash (\text{AnnCond2 } r b c) q$

| *AnnWhile*: $\llbracket r \subseteq i; i \cap b \subseteq \text{pre } c; \vdash c i; i \cap \neg b \subseteq q \rrbracket$
 $\implies \vdash (\text{AnnWhile } r b i c) q$

| *AnnAwait*: $\llbracket \text{atom-com } c; \llbracket - (r \cap b) c q \rrbracket \rrbracket \implies \vdash (\text{AnnAwait } r b c) q$

| *AnnConseq*: $\llbracket \vdash c q; q \subseteq q' \rrbracket \implies \vdash c q'$

| *Parallel*: $\llbracket \forall i < \text{length } Ts. \exists c q. Ts!i = (\text{Some } c, q) \wedge \vdash c q; \text{interfree } Ts \rrbracket$
 $\implies \llbracket - (\bigcap i \in \{i. i < \text{length } Ts\}. \text{pre}(\text{the}(\text{com}(Ts!i))))$
Parallel Ts
 $(\bigcap i \in \{i. i < \text{length } Ts\}. \text{post}(Ts!i))$

| *Basic*: $\llbracket - \{s. f s \in q\} (\text{Basic } f) q$

| *Seq*: $\llbracket \llbracket - p c1 r; \llbracket - r c2 q \rrbracket \rrbracket \implies \llbracket - p (\text{Seq } c1 c2) q$

| *Cond*: $\llbracket \llbracket - (p \cap b) c1 q; \llbracket - (p \cap \neg b) c2 q \rrbracket \rrbracket \implies \llbracket - p (\text{Cond } b c1 c2) q$

| *While*: $\llbracket \llbracket - (p \cap b) c p \rrbracket \rrbracket \implies \llbracket - p (\text{While } b i c) (p \cap \neg b)$

| *Conseq*: $\llbracket p' \subseteq p; \llbracket - p c q; q \subseteq q' \rrbracket \rrbracket \implies \llbracket - p' c q'$

1.5 Soundness

lemmas [*cong del*] = *if-weak-cong*

lemmas *ann-hoare-induct* = *oghoare-ann-hoare.induct* [*THEN conjunct2*]

lemmas *oghoare-induct* = *oghoare-ann-hoare.induct* [*THEN conjunct1*]

lemmas *AnnBasic* = *oghoare-ann-hoare.AnnBasic*

lemmas *AnnSeq* = *oghoare-ann-hoare.AnnSeq*

lemmas *AnnCond1* = *oghoare-ann-hoare.AnnCond1*

lemmas *AnnCond2* = *oghoare-ann-hoare.AnnCond2*

lemmas *AnnWhile* = *oghoare-ann-hoare.AnnWhile*

lemmas *AnnAwait* = *oghoare-ann-hoare.AnnAwait*

lemmas *AnnConseq* = *oghoare-ann-hoare.AnnConseq*

lemmas *Parallel* = *oghoare-ann-hoare.Parallel*
lemmas *Basic* = *oghoare-ann-hoare.Basic*
lemmas *Seq* = *oghoare-ann-hoare.Seq*
lemmas *Cond* = *oghoare-ann-hoare.Cond*
lemmas *While* = *oghoare-ann-hoare.While*
lemmas *Conseq* = *oghoare-ann-hoare.Conseq*

1.5.1 Soundness of the System for Atomic Programs

lemma *Basic-ntran* [*rule-format*]:
 $(\text{Basic } f, s) -Pn \rightarrow (\text{Parallel } Ts, t) \longrightarrow \text{All-None } Ts \longrightarrow t = f s$
<proof>

lemma *SEM-fwhile*: $\text{SEM } S (p \cap b) \subseteq p \implies \text{SEM } (f\text{while } b S k) p \subseteq (p \cap -b)$
<proof>

lemma *atom-hoare-sound* [*rule-format*]:
 $\| - p c q \longrightarrow \text{atom-com}(c) \longrightarrow \| = p c q$
<proof>

1.5.2 Soundness of the System for Component Programs

inductive-cases *ann-transition-cases*:

$(\text{None}, s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnBasic } r f), s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnSeq } c1 c2), s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnCond1 } r b c1 c2), s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnCond2 } r b c), s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnWhile } r b I c), s) -1 \rightarrow (c', s')$
 $(\text{Some } (\text{AnnAwait } r b c), s) -1 \rightarrow (c', s')$

Strong Soundness for Component Programs:

lemma *ann-hoare-case-analysis* [*rule-format*]: $\vdash C q' \longrightarrow$
 $((\forall r f. C = \text{AnnBasic } r f \longrightarrow (\exists q. r \subseteq \{s. f s \in q\} \wedge q \subseteq q')) \wedge$
 $(\forall c0 c1. C = \text{AnnSeq } c0 c1 \longrightarrow (\exists q. q \subseteq q' \wedge \vdash c0 \text{ pre } c1 \wedge \vdash c1 q)) \wedge$
 $(\forall r b c1 c2. C = \text{AnnCond1 } r b c1 c2 \longrightarrow (\exists q. q \subseteq q' \wedge$
 $r \cap b \subseteq \text{pre } c1 \wedge \vdash c1 q \wedge r \cap -b \subseteq \text{pre } c2 \wedge \vdash c2 q)) \wedge$
 $(\forall r b c. C = \text{AnnCond2 } r b c \longrightarrow$
 $(\exists q. q \subseteq q' \wedge r \cap b \subseteq \text{pre } c \wedge \vdash c q \wedge r \cap -b \subseteq q)) \wedge$
 $(\forall r i b c. C = \text{AnnWhile } r b i c \longrightarrow$
 $(\exists q. q \subseteq q' \wedge r \subseteq i \wedge i \cap b \subseteq \text{pre } c \wedge \vdash c i \wedge i \cap -b \subseteq q)) \wedge$
 $(\forall r b c. C = \text{AnnAwait } r b c \longrightarrow (\exists q. q \subseteq q' \wedge \| - (r \cap b) c q)))$
<proof>

lemma *Help*: $(\text{transition} \cap \{(x,y). \text{True}\}) = (\text{transition})$
<proof>

lemma *Strong-Soundness-aux-aux* [*rule-format*]:
 $(co, s) -1 \rightarrow (co', t) \longrightarrow (\forall c. co = \text{Some } c \longrightarrow s \in \text{pre } c \longrightarrow$

$(\forall q. \vdash c \ q \longrightarrow (\text{if } co' = \text{None then } t \in q \text{ else } t \in \text{pre}(\text{the } co') \wedge \vdash (\text{the } co') \ q)))$
 <proof>

lemma *Strong-Soundness-aux*: $\llbracket (\text{Some } c, s) \text{--}^* \rightarrow (co, t); s \in \text{pre } c; \vdash c \ q \rrbracket$
 $\implies \text{if } co = \text{None then } t \in q \text{ else } t \in \text{pre } (co) \wedge \vdash (co) \ q$
 <proof>

lemma *Strong-Soundness*: $\llbracket (\text{Some } c, s) \text{--}^* \rightarrow (co, t); s \in \text{pre } c; \vdash c \ q \rrbracket$
 $\implies \text{if } co = \text{None then } t \in q \text{ else } t \in \text{pre } (co)$
 <proof>

lemma *ann-hoare-sound*: $\vdash c \ q \implies \models c \ q$
 <proof>

1.5.3 Soundness of the System for Parallel Programs

lemma *Parallel-length-post-P1*: $(\text{Parallel } Ts, s) \text{--}P1 \rightarrow (R', t) \implies$
 $(\exists Rs. R' = (\text{Parallel } Rs) \wedge (\text{length } Rs) = (\text{length } Ts) \wedge$
 $(\forall i. i < \text{length } Ts \longrightarrow \text{post}(Rs \ ! \ i) = \text{post}(Ts \ ! \ i)))$
 <proof>

lemma *Parallel-length-post-PStar*: $(\text{Parallel } Ts, s) \text{--}P^* \rightarrow (R', t) \implies$
 $(\exists Rs. R' = (\text{Parallel } Rs) \wedge (\text{length } Rs) = (\text{length } Ts) \wedge$
 $(\forall i. i < \text{length } Ts \longrightarrow \text{post}(Ts \ ! \ i) = \text{post}(Rs \ ! \ i)))$
 <proof>

lemma *assertions-lemma*: $\text{pre } c \in \text{assertions } c$
 <proof>

lemma *interfree-aux1* [rule-format]:
 $(c, s) \text{--}1 \rightarrow (r, t) \longrightarrow (\text{interfree-aux}(c1, q1, c) \longrightarrow \text{interfree-aux}(c1, q1, r))$
 <proof>

lemma *interfree-aux2* [rule-format]:
 $(c, s) \text{--}1 \rightarrow (r, t) \longrightarrow (\text{interfree-aux}(c, q, a) \longrightarrow \text{interfree-aux}(r, q, a))$
 <proof>

lemma *interfree-lemma*: $\llbracket (\text{Some } c, s) \text{--}1 \rightarrow (r, t); \text{interfree } Ts ; i < \text{length } Ts;$
 $Ts \ ! \ i = (\text{Some } c, q) \rrbracket \implies \text{interfree } (Ts[i := (r, q)])$
 <proof>

Strong Soundness Theorem for Parallel Programs:

lemma *Parallel-Strong-Soundness-Seq-aux*:
 $\llbracket \text{interfree } Ts ; i < \text{length } Ts ; \text{com}(Ts \ ! \ i) = \text{Some}(\text{AnnSeq } c0 \ c1) \rrbracket$
 $\implies \text{interfree } (Ts[i := (\text{Some } c0, \text{pre } c1)])$
 <proof>

lemma *Parallel-Strong-Soundness-Seq* [rule-format (no-asm)]:
 $\llbracket \forall i < \text{length } Ts. (\text{if } \text{com}(Ts \ ! \ i) = \text{None then } b \in \text{post}(Ts \ ! \ i)) \rrbracket$

$else\ b \in pre(the(com(Ts!i))) \wedge \vdash the(com(Ts!i))\ post(Ts!i);$
 $com(Ts\ !\ i) = Some(AnnSeq\ c0\ c1); i < length\ Ts; interfree\ Ts \] \implies$
 $(\forall\ ia < length\ Ts.\ (if\ com(Ts[i:=(Some\ c0,\ pre\ c1)]!\ ia) = None$
 $then\ b \in post(Ts[i:=(Some\ c0,\ pre\ c1)]!\ ia)$
 $else\ b \in pre(the(com(Ts[i:=(Some\ c0,\ pre\ c1)]!\ ia))) \wedge$
 $\vdash the(com(Ts[i:=(Some\ c0,\ pre\ c1)]!\ ia))\ post(Ts[i:=(Some\ c0,\ pre\ c1)]!\ ia)))$
 $\wedge\ interfree\ (Ts[i:=(Some\ c0,\ pre\ c1)])$
 $\langle proof \rangle$

lemma *Parallel-Strong-Soundness-aux-aux* [rule-format]:

$(Some\ c,\ b) -1 \rightarrow (co,\ t) \rightarrow$
 $(\forall\ Ts.\ i < length\ Ts \rightarrow com(Ts\ !\ i) = Some\ c \rightarrow$
 $(\forall\ i < length\ Ts.\ (if\ com(Ts\ !\ i) = None\ then\ b \in post(Ts!i)$
 $else\ b \in pre(the(com(Ts!i))) \wedge \vdash the(com(Ts!i))\ post(Ts!i))) \rightarrow$
 $interfree\ Ts \rightarrow$
 $(\forall\ j.\ j < length\ Ts \wedge i \neq j \rightarrow (if\ com(Ts!j) = None\ then\ t \in post(Ts!j)$
 $else\ t \in pre(the(com(Ts!j))) \wedge \vdash the(com(Ts!j))\ post(Ts!j)))$
 $\langle proof \rangle$

lemma *Parallel-Strong-Soundness-aux* [rule-format]:

$\llbracket (Ts',s) -P* \rightarrow (Rs',t); Ts' = (Parallel\ Ts); interfree\ Ts;$
 $\forall\ i.\ i < length\ Ts \rightarrow (\exists\ c\ q.\ (Ts\ !\ i) = (Some\ c,\ q) \wedge s \in (pre\ c) \wedge \vdash\ c\ q) \rrbracket \implies$
 $\forall\ Rs.\ Rs' = (Parallel\ Rs) \rightarrow (\forall\ j.\ j < length\ Rs \rightarrow$
 $(if\ com(Rs\ !\ j) = None\ then\ t \in post(Ts\ !\ j)$
 $else\ t \in pre(the(com(Rs\ !\ j))) \wedge \vdash the(com(Rs\ !\ j))\ post(Ts\ !\ j))) \wedge interfree\ Rs$
 $\langle proof \rangle$

lemma *Parallel-Strong-Soundness*:

$\llbracket (Parallel\ Ts,\ s) -P* \rightarrow (Parallel\ Rs,\ t); interfree\ Ts; j < length\ Rs;$
 $\forall\ i.\ i < length\ Ts \rightarrow (\exists\ c\ q.\ Ts\ !\ i = (Some\ c,\ q) \wedge s \in pre\ c \wedge \vdash\ c\ q) \rrbracket \implies$
 $if\ com(Rs\ !\ j) = None\ then\ t \in post(Ts\ !\ j)\ else\ t \in pre\ (the(com(Rs\ !\ j)))$
 $\langle proof \rangle$

lemma *oghoare-sound* [rule-format]: $\llbracket -\ p\ c\ q \rightarrow \rrbracket = p\ c\ q$

$\langle proof \rangle$

end

1.6 Generation of Verification Conditions

theory *OG-Tactics*

imports *OG-Hoare*

begin

lemmas *ann-hoare-intros*=*AnnBasic AnnSeq AnnCond1 AnnCond2 AnnWhile AnnAwait AnnConseq*

lemmas *oghoare-intros*=*Parallel Basic Seq Cond While Conseq*

lemma *ParallelConseqRule*:

$$\begin{aligned}
& \llbracket p \subseteq (\bigcap i \in \{i. i < \text{length } Ts\}. \text{pre}(\text{the}(\text{com}(Ts ! i)))) \rrbracket; \\
& \llbracket - (\bigcap i \in \{i. i < \text{length } Ts\}. \text{pre}(\text{the}(\text{com}(Ts ! i)))) \rrbracket \\
& \quad (\text{Parallel } Ts) \\
& \quad (\bigcap i \in \{i. i < \text{length } Ts\}. \text{post}(Ts ! i)); \\
& \quad (\bigcap i \in \{i. i < \text{length } Ts\}. \text{post}(Ts ! i)) \subseteq q \rrbracket \\
& \implies \llbracket - p (\text{Parallel } Ts) q \rrbracket \\
& \langle \text{proof} \rangle
\end{aligned}$$

lemma *SkipRule*: $p \subseteq q \implies \llbracket - p (\text{Basic } id) q \rrbracket$
 $\langle \text{proof} \rangle$

lemma *BasicRule*: $p \subseteq \{s. (f s) \in q\} \implies \llbracket - p (\text{Basic } f) q \rrbracket$
 $\langle \text{proof} \rangle$

lemma *SeqRule*: $\llbracket \llbracket - p c1 r; \llbracket - r c2 q \rrbracket \rrbracket \implies \llbracket - p (\text{Seq } c1 c2) q \rrbracket$
 $\langle \text{proof} \rangle$

lemma *CondRule*:
 $\llbracket p \subseteq \{s. (s \in b \longrightarrow s \in w) \wedge (s \notin b \longrightarrow s \in w')\}; \llbracket - w c1 q; \llbracket - w' c2 q \rrbracket \rrbracket$
 $\implies \llbracket - p (\text{Cond } b c1 c2) q \rrbracket$
 $\langle \text{proof} \rangle$

lemma *WhileRule*: $\llbracket p \subseteq i; \llbracket - (i \cap b) c i; (i \cap (-b)) \subseteq q \rrbracket$
 $\implies \llbracket - p (\text{While } b i c) q \rrbracket$
 $\langle \text{proof} \rangle$

Three new proof rules for special instances of the *AnnBasic* and the *AnnAwait* commands when the transformation performed on the state is the identity, and for an *AnnAwait* command where the boolean condition is $\{s. \text{True}\}$:

lemma *AnnatomRule*:
 $\llbracket \text{atom-com}(c); \llbracket - r c q \rrbracket \rrbracket \implies \vdash (\text{AnnAwait } r \{s. \text{True}\} c) q$
 $\langle \text{proof} \rangle$

lemma *AnnskipRule*:
 $r \subseteq q \implies \vdash (\text{AnnBasic } r id) q$
 $\langle \text{proof} \rangle$

lemma *AnnwaitRule*:
 $\llbracket (r \cap b) \subseteq q \rrbracket \implies \vdash (\text{AnnAwait } r b (\text{Basic } id)) q$
 $\langle \text{proof} \rangle$

Lemmata to avoid using the definition of *map-ann-hoare*, *interfree-aux*, *interfree-swap* and *interfree* by splitting it into different cases:

lemma *interfree-aux-rule1*: *interfree-aux*(*co*, *q*, *None*)
 $\langle \text{proof} \rangle$

lemma *interfree-aux-rule2*:
 $\forall (R, r) \in (\text{atomics } a). \llbracket - (q \cap R) r q \rrbracket \implies \text{interfree-aux}(\text{None}, q, \text{Some } a)$

<proof>

lemma *interfree-aux-rule3:*

$(\forall (R, r) \in (\text{atomics } a). \Vdash (q \cap R) r \ q \wedge (\forall p \in (\text{assertions } c). \Vdash (p \cap R) r \ p))$
 $\implies \text{interfree-aux}(\text{Some } c, q, \text{Some } a)$

<proof>

lemma *AnnBasic-assertions:*

$\llbracket \text{interfree-aux}(\text{None}, r, \text{Some } a); \text{interfree-aux}(\text{None}, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnBasic } r \ f), q, \text{Some } a)$

<proof>

lemma *AnnSeq-assertions:*

$\llbracket \text{interfree-aux}(\text{Some } c1, q, \text{Some } a); \text{interfree-aux}(\text{Some } c2, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnSeq } c1 \ c2), q, \text{Some } a)$

<proof>

lemma *AnnCond1-assertions:*

$\llbracket \text{interfree-aux}(\text{None}, r, \text{Some } a); \text{interfree-aux}(\text{Some } c1, q, \text{Some } a);$
 $\text{interfree-aux}(\text{Some } c2, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnCond1 } r \ b \ c1 \ c2), q, \text{Some } a)$

<proof>

lemma *AnnCond2-assertions:*

$\llbracket \text{interfree-aux}(\text{None}, r, \text{Some } a); \text{interfree-aux}(\text{Some } c, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnCond2 } r \ b \ c), q, \text{Some } a)$

<proof>

lemma *AnnWhile-assertions:*

$\llbracket \text{interfree-aux}(\text{None}, r, \text{Some } a); \text{interfree-aux}(\text{None}, i, \text{Some } a);$
 $\text{interfree-aux}(\text{Some } c, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnWhile } r \ b \ i \ c), q, \text{Some } a)$

<proof>

lemma *AnnAwait-assertions:*

$\llbracket \text{interfree-aux}(\text{None}, r, \text{Some } a); \text{interfree-aux}(\text{None}, q, \text{Some } a) \rrbracket \implies$
 $\text{interfree-aux}(\text{Some } (\text{AnnAwait } r \ b \ c), q, \text{Some } a)$

<proof>

lemma *AnnBasic-atomics:*

$\Vdash (q \cap r) (\text{Basic } f) \ q \implies \text{interfree-aux}(\text{None}, q, \text{Some } (\text{AnnBasic } r \ f))$

<proof>

lemma *AnnSeq-atomics:*

$\llbracket \text{interfree-aux}(\text{Any}, q, \text{Some } a1); \text{interfree-aux}(\text{Any}, q, \text{Some } a2) \rrbracket \implies$
 $\text{interfree-aux}(\text{Any}, q, \text{Some } (\text{AnnSeq } a1 \ a2))$

<proof>

lemma *AnnCond1-atomics:*

$\llbracket \text{interfree-aux}(\text{Any}, q, \text{Some } a1); \text{interfree-aux}(\text{Any}, q, \text{Some } a2) \rrbracket \Longrightarrow$
 $\text{interfree-aux}(\text{Any}, q, \text{Some } (\text{AnnCond1 } r \ b \ a1 \ a2))$
 <proof>

lemma *AnnCond2-atomics:*

$\text{interfree-aux}(\text{Any}, q, \text{Some } a) \Longrightarrow \text{interfree-aux}(\text{Any}, q, \text{Some } (\text{AnnCond2 } r \ b \ a))$
 <proof>

lemma *AnnWhile-atomics:* $\text{interfree-aux}(\text{Any}, q, \text{Some } a)$

$\Longrightarrow \text{interfree-aux}(\text{Any}, q, \text{Some } (\text{AnnWhile } r \ b \ i \ a))$
 <proof>

lemma *Annatom-atomics:*

$\llbracket - \ (q \cap r) \ a \ q \Longrightarrow \text{interfree-aux}(\text{None}, q, \text{Some } (\text{AnnAwait } r \ \{x. \text{True}\} \ a)) \rrbracket$
 <proof>

lemma *AnnAwait-atomics:*

$\llbracket - \ (q \cap (r \cap b)) \ a \ q \Longrightarrow \text{interfree-aux}(\text{None}, q, \text{Some } (\text{AnnAwait } r \ b \ a)) \rrbracket$
 <proof>

definition *interfree-swap* :: $('a \ \text{ann-triple-op} * ('a \ \text{ann-triple-op}) \ \text{list}) \Rightarrow \text{bool}$ **where**

$\text{interfree-swap} == \lambda(x, xs). \forall y \in \text{set } xs. \text{interfree-aux}(\text{com } x, \text{post } x, \text{com } y)$
 $\wedge \text{interfree-aux}(\text{com } y, \text{post } y, \text{com } x)$

lemma *interfree-swap-Empty:* $\text{interfree-swap}(x, [])$

<proof>

lemma *interfree-swap-List:*

$\llbracket \text{interfree-aux}(\text{com } x, \text{post } x, \text{com } y);$
 $\text{interfree-aux}(\text{com } y, \text{post } y, \text{com } x); \text{interfree-swap}(x, xs) \rrbracket$
 $\Longrightarrow \text{interfree-swap}(x, y \# xs)$
 <proof>

lemma *interfree-swap-Map:* $\forall k. i \leq k \wedge k < j \longrightarrow \text{interfree-aux}(\text{com } x, \text{post } x, c \ k)$

$\wedge \text{interfree-aux}(c \ k, Q \ k, \text{com } x)$
 $\Longrightarrow \text{interfree-swap}(x, \text{map } (\lambda k. (c \ k, Q \ k)) [i..<j])$
 <proof>

lemma *interfree-Empty:* $\text{interfree } []$

<proof>

lemma *interfree-List:*

$\llbracket \text{interfree-swap}(x, xs); \text{interfree } xs \rrbracket \Longrightarrow \text{interfree } (x \# xs)$
 <proof>

lemma *interfree-Map:*

$(\forall i \ j. a \leq i \wedge i < b \wedge a \leq j \wedge j < b \wedge i \neq j \longrightarrow \text{interfree-aux}(c \ i, Q \ i, c \ j))$
 $\Longrightarrow \text{interfree}(\text{map } (\lambda k. (c \ k, Q \ k)) [a..<b])$

$\langle proof \rangle$

definition *map-ann-hoare* :: (('a ann-com-op * 'a assn) list) \Rightarrow bool ($\langle [\vdash] \rightarrow [0]$
45) **where**
 $[\vdash] Ts == (\forall i < length Ts. \exists c q. Ts!i = (Some c, q) \wedge \vdash c q)$

lemma *MapAnnEmpty*: $[\vdash] []$
 $\langle proof \rangle$

lemma *MapAnnList*: $[\vdash c q ; [\vdash] xs] \Longrightarrow [\vdash] (Some c, q) \# xs$
 $\langle proof \rangle$

lemma *MapAnnMap*:
 $\forall k. i < k \wedge k < j \longrightarrow \vdash (c k) (Q k) \Longrightarrow [\vdash] map (\lambda k. (Some (c k), Q k)) [i..<j]$
 $\langle proof \rangle$

lemma *ParallelRule*: $[\vdash] Ts ; interfree Ts]$
 $\Longrightarrow \parallel - (\bigcap i \in \{i. i < length Ts\}. pre(the(com(Ts!i))))$
Parallel Ts
 $(\bigcap i \in \{i. i < length Ts\}. post(Ts!i))$
 $\langle proof \rangle$

The following are some useful lemmas and simplification tactics to control which theorems are used to simplify at each moment, so that the original input does not suffer any unexpected transformation.

lemma *Compl-Collect*: $-(Collect b) = \{x. \neg(b x)\}$
 $\langle proof \rangle$

lemma *list-length*: $length [] = 0$ $length (x \# xs) = Suc(length xs)$
 $\langle proof \rangle$

lemma *list-lemmas*: $length [] = 0$ $length (x \# xs) = Suc(length xs)$
 $(x \# xs) ! 0 = x$ $(x \# xs) ! Suc n = xs ! n$
 $\langle proof \rangle$

lemma *le-Suc-eq-insert*: $\{i. i < Suc n\} = insert n \{i. i < n\}$
 $\langle proof \rangle$

lemmas *primrecdef-list* = *pre.simps assertions.simps atomics.simps atom-com.simps*

lemmas *my-simp-list* = *list-lemmas fst-conv snd-conv*
not-less0 refl le-Suc-eq-insert Suc-not-Zero Zero-not-Suc nat.inject
Collect-mem-eq ball-simps option.simps primrecdef-list

lemmas *ParallelConseq-list* = *INTER-eq Collect-conj-eq length-map length-upt length-append*

$\langle ML \rangle$

The following tactic applies *tac* to each conjunct in a subgoal of the form $A \Longrightarrow a1 \wedge a2 \wedge \dots \wedge an$ returning n subgoals, one for each conjunct:

$\langle ML \rangle$

Tactic for the generation of the verification conditions

The tactic basically uses two subtactics:

HoareRuleTac is called at the level of parallel programs, it uses the `ParallelTac` to solve parallel composition of programs. This verification has two parts, namely, (1) all component programs are correct and (2) they are interference free. *HoareRuleTac* is also called at the level of atomic regions, i.e. `< >` and `AWAIT b THEN - END`, and at each interference freedom test.

AnnHoareRuleTac is for component programs which are annotated programs and so, there are not unknown assertions (no need to use the parameter `precond`, see NOTE).

NOTE: `precond (::bool)` informs if the subgoal has the form $\parallel - ?p \ c \ q$, in this case we have `precond=False` and the generated verification condition would have the form $?p \subseteq \dots$ which can be solved by *rtac subset-refl*, if `True` we proceed to simplify it using the simplification tactics above.

<ML>

The final tactic is given the name *oghoare*:

<ML>

Notice that the tactic for parallel programs *oghoare-tac* is initially invoked with the value *true* for the parameter *precond*.

Parts of the tactic can be also individually used to generate the verification conditions for annotated sequential programs and to generate verification conditions out of interference freedom tests:

<ML>

The so defined ML tactics are then “exported” to be used in Isabelle proofs.

<ML>

Tactics useful for dealing with the generated verification conditions:

<ML>

end

1.7 Concrete Syntax

theory *Quote-Antiquote* **imports** *Main* **begin**

syntax

-quote :: $'b \Rightarrow ('a \Rightarrow 'b)$ ($\langle \langle - \rangle \rangle$ [0] 1000)
-antiquote :: $('a \Rightarrow 'b) \Rightarrow 'b$ ($\langle ' - \rangle$ [1000] 1000)

-Assert :: 'a \Rightarrow 'a set ($\langle\{\{-\}\rangle$ [0] 1000)

translations

$\{\{b\}\} \rightarrow \text{CONST Collect } \langle\langle b \rangle\rangle$

$\langle ML \rangle$

end

theory OG-Syntax

imports OG-Tactics Quote-Antiquote

begin

Syntax for commands and for assertions and boolean expressions in commands *com* and annotated commands *ann-com*.

abbreviation Skip :: 'a com ($\langle\text{SKIP}\rangle$ 63)

where SKIP \equiv Basic id

abbreviation AnnSkip :: 'a assn \Rightarrow 'a ann-com ($\langle\text{//SKIP}\rangle$ [90] 63)

where r SKIP \equiv AnnBasic r id

notation

Seq ($\langle\langle -, / \rightarrow$ [55, 56] 55) **and**

AnnSeq ($\langle\langle -; / \rightarrow$ [60,61] 60)

syntax

-Assign :: idt \Rightarrow 'b \Rightarrow 'a com ($\langle\langle ' := / - \rangle\rangle$ [70, 65] 61)

-AnnAssign :: 'a assn \Rightarrow idt \Rightarrow 'b \Rightarrow 'a com ($\langle\langle - ' := / - \rangle\rangle$ [90,70,65] 61)

translations

'x := a \rightarrow CONST Basic $\langle\langle '(-\text{update-name } x (\lambda-. a)) \rangle\rangle$

r 'x := a \rightarrow CONST AnnBasic r $\langle\langle '(-\text{update-name } x (\lambda-. a)) \rangle\rangle$

syntax

-AnnCond1 :: 'a assn \Rightarrow 'a bexp \Rightarrow 'a ann-com \Rightarrow 'a ann-com \Rightarrow 'a ann-com
($\langle\langle - //IF - /THEN - /ELSE - /FI \rangle\rangle$ [90,0,0,0] 61)

-AnnCond2 :: 'a assn \Rightarrow 'a bexp \Rightarrow 'a ann-com \Rightarrow 'a ann-com
($\langle\langle - //IF - /THEN - /FI \rangle\rangle$ [90,0,0] 61)

-AnnWhile :: 'a assn \Rightarrow 'a bexp \Rightarrow 'a assn \Rightarrow 'a ann-com \Rightarrow 'a ann-com
($\langle\langle - //WHILE - /INV - //DO - //OD \rangle\rangle$ [90,0,0,0] 61)

-AnnAwait :: 'a assn \Rightarrow 'a bexp \Rightarrow 'a com \Rightarrow 'a ann-com
($\langle\langle - //AWAIT - /THEN /- /END \rangle\rangle$ [90,0,0] 61)

-AnnAtom :: 'a assn \Rightarrow 'a com \Rightarrow 'a ann-com ($\langle\langle - // \langle - \rangle \rangle$ [90,0] 61)

-AnnWait :: 'a assn \Rightarrow 'a bexp \Rightarrow 'a ann-com ($\langle\langle - //WAIT - END \rangle\rangle$ [90,0] 61)

-Cond :: 'a bexp \Rightarrow 'a com \Rightarrow 'a com \Rightarrow 'a com
($\langle\langle (0IF - / THEN - / ELSE - / FI) \rangle\rangle$ [0, 0, 0] 61)

-Cond2 :: 'a bexp \Rightarrow 'a com \Rightarrow 'a com ($\langle\langle IF - THEN - FI \rangle\rangle$ [0,0] 56)

-While-inv :: 'a bexp \Rightarrow 'a assn \Rightarrow 'a com \Rightarrow 'a com
($\langle\langle (0WHILE - / INV - //DO - /OD) \rangle\rangle$ [0, 0, 0] 61)

-While :: 'a bexp \Rightarrow 'a com \Rightarrow 'a com
 ($\langle 0\text{WHILE } - // \text{DO } - // \text{OD} \rangle$ [0, 0] 61)

translations

$IF\ b\ THEN\ c1\ ELSE\ c2\ FI \rightarrow CONST\ Cond\ \{b\}\ c1\ c2$
 $IF\ b\ THEN\ c\ FI \Leftrightarrow IF\ b\ THEN\ c\ ELSE\ SKIP\ FI$
 $WHILE\ b\ INV\ i\ DO\ c\ OD \rightarrow CONST\ While\ \{b\}\ i\ c$
 $WHILE\ b\ DO\ c\ OD \Leftrightarrow WHILE\ b\ INV\ CONST\ undefined\ DO\ c\ OD$

$r\ IF\ b\ THEN\ c1\ ELSE\ c2\ FI \rightarrow CONST\ AnnCond1\ r\ \{b\}\ c1\ c2$
 $r\ IF\ b\ THEN\ c\ FI \rightarrow CONST\ AnnCond2\ r\ \{b\}\ c$
 $r\ WHILE\ b\ INV\ i\ DO\ c\ OD \rightarrow CONST\ AnnWhile\ r\ \{b\}\ i\ c$
 $r\ AWAIT\ b\ THEN\ c\ END \rightarrow CONST\ AnnAwait\ r\ \{b\}\ c$
 $r\ \langle c \rangle \Leftrightarrow r\ AWAIT\ CONST\ True\ THEN\ c\ END$
 $r\ WAIT\ b\ END \Leftrightarrow r\ AWAIT\ b\ THEN\ SKIP\ END$

nonterminal prgs

syntax

-PAR :: prgs \Rightarrow 'a ($\langle COBEGIN // - // COEND \rangle$ [57] 56)
 -prg :: ['a, 'a] \Rightarrow prgs ($\langle - // - \rangle$ [60, 90] 57)
 -prgs :: ['a, 'a, prgs] \Rightarrow prgs ($\langle - // - // - // - \rangle$ [60, 90, 57] 57)
 -prg-scheme :: ['a, 'a, 'a, 'a, 'a] \Rightarrow prgs
 ($\langle SCHEME [- \leq - < -] - // - \rangle$ [0, 0, 0, 60, 90] 57)

translations

$-prg\ c\ q \Leftrightarrow [(CONST\ Some\ c,\ q)]$
 $-prgs\ c\ q\ ps \Leftrightarrow (CONST\ Some\ c,\ q)\ \#\ ps$
 $-PAR\ ps \Leftrightarrow CONST\ Parallel\ ps$
 $-prg-scheme\ j\ i\ k\ c\ q \Leftrightarrow CONST\ map\ (\lambda i.\ (CONST\ Some\ c,\ q))\ [j..<k]$

$\langle ML \rangle$

end

1.8 Examples

theory *OG-Examples* imports *OG-Syntax* begin

1.8.1 Mutual Exclusion

Peterson's Algorithm I

Eike Best. "Semantics of Sequential and Parallel Programs", page 217.

record *Petersons-mutex-1* =
 pr1 :: nat
 pr2 :: nat

in1 :: bool
in2 :: bool
hold :: nat

lemma *Petersons-mutex-1*:

$\parallel - \{ \text{'pr1}=0 \wedge \neg \text{'in1} \wedge \text{'pr2}=0 \wedge \neg \text{'in2} \}$
 COBEGIN $\{ \text{'pr1}=0 \wedge \neg \text{'in1} \}$
 WHILE True INV $\{ \text{'pr1}=0 \wedge \neg \text{'in1} \}$
 DO
 $\{ \text{'pr1}=0 \wedge \neg \text{'in1} \} \langle \text{'in1}:=\text{True},, \text{'pr1}:=1 \rangle;;$
 $\{ \text{'pr1}=1 \wedge \text{'in1} \} \langle \text{'hold}:=1,, \text{'pr1}:=2 \rangle;;$
 $\{ \text{'pr1}=2 \wedge \text{'in1} \wedge (\text{'hold}=1 \vee \text{'hold}=2 \wedge \text{'pr2}=2) \}$
 AWAIT $(\neg \text{'in2} \vee \neg(\text{'hold}=1))$ THEN $\text{'pr1}:=3$ END;;
 $\{ \text{'pr1}=3 \wedge \text{'in1} \wedge (\text{'hold}=1 \vee \text{'hold}=2 \wedge \text{'pr2}=2) \}$
 $\langle \text{'in1}:=\text{False},, \text{'pr1}:=0 \rangle$
 OD $\{ \text{'pr1}=0 \wedge \neg \text{'in1} \}$
 \parallel
 $\{ \text{'pr2}=0 \wedge \neg \text{'in2} \}$
 WHILE True INV $\{ \text{'pr2}=0 \wedge \neg \text{'in2} \}$
 DO
 $\{ \text{'pr2}=0 \wedge \neg \text{'in2} \} \langle \text{'in2}:=\text{True},, \text{'pr2}:=1 \rangle;;$
 $\{ \text{'pr2}=1 \wedge \text{'in2} \} \langle \text{'hold}:=2,, \text{'pr2}:=2 \rangle;;$
 $\{ \text{'pr2}=2 \wedge \text{'in2} \wedge (\text{'hold}=2 \vee (\text{'hold}=1 \wedge \text{'pr1}=2)) \}$
 AWAIT $(\neg \text{'in1} \vee \neg(\text{'hold}=2))$ THEN $\text{'pr2}:=3$ END;;
 $\{ \text{'pr2}=3 \wedge \text{'in2} \wedge (\text{'hold}=2 \vee (\text{'hold}=1 \wedge \text{'pr1}=2)) \}$
 $\langle \text{'in2}:=\text{False},, \text{'pr2}:=0 \rangle$
 OD $\{ \text{'pr2}=0 \wedge \neg \text{'in2} \}$
 COEND
 $\{ \text{'pr1}=0 \wedge \neg \text{'in1} \wedge \text{'pr2}=0 \wedge \neg \text{'in2} \}$
 <proof>

Peterson's Algorithm II: A Busy Wait Solution

Apt and Olderog. "Verification of sequential and concurrent Programs", page 282.

record *Busy-wait-mutex* =

flag1 :: bool
flag2 :: bool
turn :: nat
after1 :: bool
after2 :: bool

lemma *Busy-wait-mutex*:

$\parallel - \{ \text{True} \}$
 $\text{'flag1}:=\text{False},, \text{'flag2}:=\text{False},,$
 COBEGIN $\{ \neg \text{'flag1} \}$
 WHILE True
 INV $\{ \neg \text{'flag1} \}$
 DO $\{ \neg \text{'flag1} \} \langle \text{'flag1}:=\text{True},, \text{'after1}:=\text{False} \rangle;;$

```

    { 'flag1 ∧ ¬ 'after1 } ⟨ 'turn:=1,, 'after1:=True ⟩;;
    { 'flag1 ∧ 'after1 ∧ ('turn=1 ∨ 'turn=2) }
    WHILE ¬('flag2 → 'turn=2)
    INV { 'flag1 ∧ 'after1 ∧ ('turn=1 ∨ 'turn=2) }
    DO { 'flag1 ∧ 'after1 ∧ ('turn=1 ∨ 'turn=2) } SKIP OD;;
    { 'flag1 ∧ 'after1 ∧ ('flag2 ∧ 'after2 → 'turn=2) }
    'flag1:=False
  OD
  {False}
||
  {¬ 'flag2}
  WHILE True
  INV {¬ 'flag2}
  DO {¬ 'flag2} ⟨ 'flag2:=True,, 'after2:=False ⟩;;
    { 'flag2 ∧ ¬ 'after2 } ⟨ 'turn:=2,, 'after2:=True ⟩;;
    { 'flag2 ∧ 'after2 ∧ ('turn=1 ∨ 'turn=2) }
    WHILE ¬('flag1 → 'turn=1)
    INV { 'flag2 ∧ 'after2 ∧ ('turn=1 ∨ 'turn=2) }
    DO { 'flag2 ∧ 'after2 ∧ ('turn=1 ∨ 'turn=2) } SKIP OD;;
    { 'flag2 ∧ 'after2 ∧ ('flag1 ∧ 'after1 → 'turn=1) }
    'flag2:=False
  OD
  {False}
COEND
{False}
⟨proof⟩

```

Peterson's Algorithm III: A Solution using Semaphores

```

record Semaphores-mutex =
  out :: bool
  who :: nat

```

lemma Semaphores-mutex:

```

||- {i≠j}
  'out:=True ,,
  COBEGIN {i≠j}
    WHILE True INV {i≠j}
    DO {i≠j} AWAIT 'out THEN 'out:=False,, 'who:=i END;;
    {¬ 'out ∧ 'who=i ∧ i≠j} 'out:=True OD
  {False}
||
  {i≠j}
  WHILE True INV {i≠j}
  DO {i≠j} AWAIT 'out THEN 'out:=False,, 'who:=j END;;
  {¬ 'out ∧ 'who=j ∧ i≠j} 'out:=True OD
  {False}
COEND
{False}

```


<proof>

Peterson's Algorithm III: Parameterized version:

lemma *Semaphores-parameterized-mutex:*

```
0 < n ==> || - { True }
'out := True ,,
COBEGIN
SCHEME [0 ≤ i < n]
  { True }
  WHILE True INV { True }
  DO { True } AWAIT 'out THEN 'out := False,, 'who := i END;;
  { ¬ 'out ∧ 'who = i } 'out := True OD
  { False }
COEND
{ False }
<proof>
```

The Ticket Algorithm

record *Ticket-mutex* =

```
num :: nat
nextv :: nat
turn :: nat list
index :: nat
```

lemma *Ticket-mutex:*

```
[[ 0 < n; I = «n = length 'turn ∧ 0 < 'nextv ∧ (∀ k l. k < n ∧ l < n ∧ k ≠ l
  → 'turn!k < 'num ∧ ('turn!k = 0 ∨ 'turn!k ≠ 'turn!l))» ]]
==> || - { n = length 'turn }
'index := 0,,
WHILE 'index < n INV { n = length 'turn ∧ (∀ i < 'index. 'turn!i = 0) }
DO 'turn := 'turn['index := 0],, 'index := 'index + 1 OD,,
'num := 1 ,, 'nextv := 1 ,,
COBEGIN
SCHEME [0 ≤ i < n]
  { 'I }
  WHILE True INV { 'I }
  DO { 'I } < 'turn := 'turn[i := 'num],, 'num := 'num + 1 >;
  { 'I } WAIT 'turn!i = 'nextv END;;
  { 'I ∧ 'turn!i = 'nextv } 'nextv := 'nextv + 1
  OD
  { False }
COEND
{ False }
<proof>
```

1.8.2 Parallel Zero Search

Synchronized Zero Search. Zero-6

```

record Zero-search =
  turn :: nat
  found :: bool
  x :: nat
  y :: nat

```

lemma Zero-search:

```

[[I1 = « a ≤ 'x ∧ ('found → (a < 'x ∧ f('x)=0) ∨ ('y ≤ a ∧ f('y)=0))
  ∧ (¬'found ∧ a < 'x → f('x)≠0) » ;
  I2 = « 'y ≤ a+1 ∧ ('found → (a < 'x ∧ f('x)=0) ∨ ('y ≤ a ∧ f('y)=0))
  ∧ (¬'found ∧ 'y ≤ a → f('y)≠0) » ]] ⇒
||- {∃ u. f(u)=0}
' turn:=1,, ' found:= False,,
' x:=a,, ' y:=a+1 ,,
COBEGIN {I1}
  WHILE ¬' found
  INV {I1}
  DO {a ≤ 'x ∧ ('found → 'y ≤ a ∧ f('y)=0) ∧ (a < 'x → f('x)≠0)}
    WAIT ' turn=1 END;;
    {a ≤ 'x ∧ ('found → 'y ≤ a ∧ f('y)=0) ∧ (a < 'x → f('x)≠0)}
    ' turn:=2;;
    {a ≤ 'x ∧ ('found → 'y ≤ a ∧ f('y)=0) ∧ (a < 'x → f('x)≠0)}
    < ' x:=' x+1,,
      IF f('x)=0 THEN ' found:=True ELSE SKIP FI)
  OD;;
  {I1 ∧ ' found}
  ' turn:=2
  {I1 ∧ ' found}
||
  {I2}
  WHILE ¬' found
  INV {I2}
  DO {'y ≤ a+1 ∧ ('found → a < 'x ∧ f('x)=0) ∧ ('y ≤ a → f('y)≠0)}
    WAIT ' turn=2 END;;
    {'y ≤ a+1 ∧ ('found → a < 'x ∧ f('x)=0) ∧ ('y ≤ a → f('y)≠0)}
    ' turn:=1;;
    {'y ≤ a+1 ∧ ('found → a < 'x ∧ f('x)=0) ∧ ('y ≤ a → f('y)≠0)}
    < ' y:=' y - 1,,
      IF f('y)=0 THEN ' found:=True ELSE SKIP FI)
  OD;;
  {I2 ∧ ' found}
  ' turn:=1
  {I2 ∧ ' found}
COEND
{f('x)=0 ∨ f('y)=0}
<proof>

```

Easier Version: without AWAIT. Apt and Olderog. page 256:

lemma *Zero-Search-2*:

$$\begin{aligned} & \llbracket I1 = \langle a \leq 'x \wedge ('found \longrightarrow (a < 'x \wedge f('x) = 0) \vee ('y \leq a \wedge f('y) = 0)) \\ & \quad \wedge (\neg 'found \wedge a < 'x \longrightarrow f('x) \neq 0) \rangle \rrbracket; \\ & I2 = \langle 'y \leq a + 1 \wedge ('found \longrightarrow (a < 'x \wedge f('x) = 0) \vee ('y \leq a \wedge f('y) = 0)) \\ & \quad \wedge (\neg 'found \wedge 'y \leq a \longrightarrow f('y) \neq 0) \rangle \rrbracket \implies \\ & \parallel - \{ \exists u. f(u) = 0 \} \\ & \quad 'found := False, \\ & \quad 'x := a, 'y := a + 1, \\ & \text{COBEGIN } \{ I1 \} \\ & \quad \text{WHILE } \neg 'found \\ & \quad \text{INV } \{ I1 \} \\ & \quad \text{DO } \{ a \leq 'x \wedge ('found \longrightarrow 'y \leq a \wedge f('y) = 0) \wedge (a < 'x \longrightarrow f('x) \neq 0) \} \\ & \quad \quad \langle 'x := 'x + 1, \text{IF } f('x) = 0 \text{ THEN } 'found := True \text{ ELSE SKIP FI} \rangle \\ & \quad \text{OD} \\ & \quad \{ I1 \wedge 'found \} \\ & \parallel \\ & \quad \{ I2 \} \\ & \quad \text{WHILE } \neg 'found \\ & \quad \text{INV } \{ I2 \} \\ & \quad \text{DO } \{ 'y \leq a + 1 \wedge ('found \longrightarrow a < 'x \wedge f('x) = 0) \wedge ('y \leq a \longrightarrow f('y) \neq 0) \} \\ & \quad \quad \langle 'y := ('y - 1), \text{IF } f('y) = 0 \text{ THEN } 'found := True \text{ ELSE SKIP FI} \rangle \\ & \quad \text{OD} \\ & \quad \{ I2 \wedge 'found \} \\ & \text{COEND} \\ & \{ f('x) = 0 \vee f('y) = 0 \} \\ & \langle \text{proof} \rangle \end{aligned}$$

1.8.3 Producer/Consumer

Previous lemmas

lemma *nat-lemma2*: $\llbracket b = m * (n :: nat) + t; a = s * n + u; t = u; b - a < n \rrbracket \implies m \leq s$
 $\langle \text{proof} \rangle$

lemma *mod-lemma*: $\llbracket (c :: nat) \leq a; a < b; b - c < n \rrbracket \implies b \text{ mod } n \neq a \text{ mod } n$
 $\langle \text{proof} \rangle$

Producer/Consumer Algorithm

record *Producer-consumer* =

ins :: nat
outs :: nat
li :: nat
lj :: nat
vx :: nat
vy :: nat
buffer :: nat list
b :: nat list

The whole proof takes aprox. 4 minutes.

lemma *Producer-consumer*:

```

[[INIT = «0 < length a ∧ 0 < length 'buffer ∧ length 'b = length a» ;
 I = «(∀ k < 'ins. 'outs ≤ k → (a ! k) = 'buffer ! (k mod (length 'buffer))) ∧
      'outs ≤ 'ins ∧ 'ins - 'outs ≤ length 'buffer» ;
 I1 = «'I ∧ 'li ≤ length a» ;
 p1 = «'I1 ∧ 'li = 'ins» ;
 I2 = «'I ∧ (∀ k < 'lj. (a ! k) = ('b ! k)) ∧ 'lj ≤ length a» ;
 p2 = «'I2 ∧ 'lj = 'outs» ]] ⇒
||- { 'INIT }
'ins:=0,, 'outs:=0,, 'li:=0,, 'lj:=0,,
COBEGIN { 'p1 ∧ 'INIT }
  WHILE 'li < length a
    INV { 'p1 ∧ 'INIT }
    DO { 'p1 ∧ 'INIT ∧ 'li < length a }
      'vx := (a ! 'li);
      { 'p1 ∧ 'INIT ∧ 'li < length a ∧ 'vx = (a ! 'li) }
      WAIT 'ins - 'outs < length 'buffer END;;
      { 'p1 ∧ 'INIT ∧ 'li < length a ∧ 'vx = (a ! 'li)
        ∧ 'ins - 'outs < length 'buffer }
      'buffer := (list-update 'buffer ('ins mod (length 'buffer)) 'vx);
      { 'p1 ∧ 'INIT ∧ 'li < length a
        ∧ (a ! 'li) = ('buffer ! ('ins mod (length 'buffer)))
        ∧ 'ins - 'outs < length 'buffer }
      'ins := 'ins + 1;;
      { 'I1 ∧ 'INIT ∧ ('li + 1) = 'ins ∧ 'li < length a }
      'li := 'li + 1
    OD
  { 'p1 ∧ 'INIT ∧ 'li = length a }
||
{ 'p2 ∧ 'INIT }
  WHILE 'lj < length a
    INV { 'p2 ∧ 'INIT }
    DO { 'p2 ∧ 'lj < length a ∧ 'INIT }
      WAIT 'outs < 'ins END;;
      { 'p2 ∧ 'lj < length a ∧ 'outs < 'ins ∧ 'INIT }
      'vy := ('buffer ! ('outs mod (length 'buffer)));
      { 'p2 ∧ 'lj < length a ∧ 'outs < 'ins ∧ 'vy = (a ! 'lj) ∧ 'INIT }
      'outs := 'outs + 1;;
      { 'I2 ∧ ('lj + 1) = 'outs ∧ 'lj < length a ∧ 'vy = (a ! 'lj) ∧ 'INIT }
      'b := (list-update 'b 'lj 'vy);
      { 'I2 ∧ ('lj + 1) = 'outs ∧ 'lj < length a ∧ (a ! 'lj) = ('b ! 'lj) ∧ 'INIT }
      'lj := 'lj + 1
    OD
  { 'p2 ∧ 'lj = length a ∧ 'INIT }
COEND
{ ∀ k < length a. (a ! k) = ('b ! k) }
⟨proof⟩

```

1.8.4 Parameterized Examples

Set Elements of an Array to Zero

record *Example1* =
 a :: nat ⇒ nat

lemma *Example1*:
 ||- {True}
 COBEGIN SCHEME [0 ≤ *i* < *n*] {True} 'a := 'a (i := 0) { 'a i = 0 } COEND
 {∀ *i* < *n*. 'a i = 0}
 ⟨proof⟩

Same example with lists as auxiliary variables.

record *Example1-list* =
 A :: nat list

lemma *Example1-list*:
 ||- {*n* < length 'A}
 COBEGIN
 SCHEME [0 ≤ *i* < *n*] {*n* < length 'A} 'A := 'A[i := 0] { 'A i = 0 }
 COEND
 {∀ *i* < *n*. 'A i = 0}
 ⟨proof⟩

Increment a Variable in Parallel

First some lemmas about summation properties.

lemma *Example2-lemma2-aux*: !!*b*. *j* < *n* ⇒
 (∑ *i* = 0 .. < *n*. (*b* i :: nat)) =
 (∑ *i* = 0 .. < *j*. *b* i) + *b* *j* + (∑ *i* = 0 .. < *n* - (Suc *j*). *b* (Suc *j* + *i*))
 ⟨proof⟩

lemma *Example2-lemma2-aux2*:
 !!*b*. *j* ≤ *s* ⇒ (∑ *i* :: nat = 0 .. < *j*. (*b* (s := t)) i) = (∑ *i* = 0 .. < *j*. *b* i)
 ⟨proof⟩

lemma *Example2-lemma2*:
 !!*b*. [*j* < *n*; *b* *j* = 0] ⇒ Suc (∑ *i* :: nat = 0 .. < *n*. *b* i) = (∑ *i* = 0 .. < *n*. (*b* (j := Suc 0))
 i)
 ⟨proof⟩

record *Example2* =
 c :: nat ⇒ nat
 x :: nat

lemma *Example-2*: 0 < *n* ⇒
 ||- { 'x = 0 ∧ (∑ *i* = 0 .. < *n*. 'c i) = 0 }
 COBEGIN

```

SCHEME [0 ≤ i < n]
{ { x = (∑ i=0..<n. c i) ∧ c i = 0 }
  { x := x + (Suc 0),, c := c (i := (Suc 0)) }
  { x = (∑ i=0..<n. c i) ∧ c i = (Suc 0) }
COEND
{ { x = n }
  { proof }

```

end

Chapter 2

Case Study: Single and Multi-Mutator Garbage Collection Algorithms

2.1 Formalization of the Memory

theory *Graph* imports *Main* begin

datatype *node* = *Black* | *White*

type-synonym *nodes* = *node list*

type-synonym *edge* = *nat* × *nat*

type-synonym *edges* = *edge list*

consts *Roots* :: *nat set*

definition *Proper-Roots* :: *nodes* ⇒ *bool* **where**

$Proper-Roots\ M \equiv Roots \neq \{\} \wedge Roots \subseteq \{i. i < length\ M\}$

definition *Proper-Edges* :: (*nodes* × *edges*) ⇒ *bool* **where**

$Proper-Edges \equiv (\lambda(M, E). \forall i < length\ E. fst(E!i) < length\ M \wedge snd(E!i) < length\ M)$

definition *BtoW* :: (*edge* × *nodes*) ⇒ *bool* **where**

$BtoW \equiv (\lambda(e, M). (M!fst\ e) = Black \wedge (M!snd\ e) \neq Black)$

definition *Blacks* :: *nodes* ⇒ *nat set* **where**

$Blacks\ M \equiv \{i. i < length\ M \wedge M!i = Black\}$

definition *Reach* :: *edges* ⇒ *nat set* **where**

$Reach\ E \equiv \{x. (\exists path. 1 < length\ path \wedge path!(length\ path - 1) \in Roots \wedge x = path!0 \wedge (\forall i < length\ path - 1. (\exists j < length\ E. E!j = (path!(i+1), path!i)))) \vee x \in Roots\}$

Reach: the set of reachable nodes is the set of Roots together with the nodes reachable from some Root by a path represented by a list of nodes (at least two since we traverse at least one edge), where two consecutive nodes correspond to an edge in E.

2.1.1 Proofs about Graphs

lemmas *Graph-defs*= *Blacks-def* *Proper-Roots-def* *Proper-Edges-def* *BtoW-def*
declare *Graph-defs* [*simp*]

Graph 1

lemma *Graph1-aux* [*rule-format*]:

$\llbracket \text{Roots} \subseteq \text{Blacks } M; \forall i < \text{length } E. \neg \text{BtoW}(E!i, M) \rrbracket$
 $\implies 1 < \text{length path} \longrightarrow (\text{path}!(\text{length path} - 1)) \in \text{Roots} \longrightarrow$
 $(\forall i < \text{length path} - 1. (\exists j. j < \text{length } E \wedge E!j = (\text{path}!(\text{Suc } i), \text{path}!i)))$
 $\longrightarrow M!(\text{path}!0) = \text{Black}$
 $\langle \text{proof} \rangle$

lemma *Graph1*:

$\llbracket \text{Roots} \subseteq \text{Blacks } M; \text{Proper-Edges}(M, E); \forall i < \text{length } E. \neg \text{BtoW}(E!i, M) \rrbracket$
 $\implies \text{Reach } E \subseteq \text{Blacks } M$
 $\langle \text{proof} \rangle$

Graph 2

lemma *Ex-first-occurrence* [*rule-format*]:

$P (n::\text{nat}) \longrightarrow (\exists m. P m \wedge (\forall i. i < m \longrightarrow \neg P i))$
 $\langle \text{proof} \rangle$

lemma *Compl-lemma*: $(n::\text{nat}) \leq l \implies (\exists m. m \leq l \wedge n = l - m)$

$\langle \text{proof} \rangle$

lemma *Ex-last-occurrence*:

$\llbracket P (n::\text{nat}); n \leq l \rrbracket \implies (\exists m. P (l - m) \wedge (\forall i. i < m \longrightarrow \neg P (l - i)))$
 $\langle \text{proof} \rangle$

lemma *Graph2*:

$\llbracket T \in \text{Reach } E; R < \text{length } E \rrbracket \implies T \in \text{Reach } (E[R := (\text{fst}(E!R), T)])$
 $\langle \text{proof} \rangle$

Graph 3

declare *min.absorb1* [*simp*] *min.absorb2* [*simp*]

lemma *Graph3*:

$\llbracket T \in \text{Reach } E; R < \text{length } E \rrbracket \implies \text{Reach}(E[R := (\text{fst}(E!R), T)]) \subseteq \text{Reach } E$
 $\langle \text{proof} \rangle$

Graph 4

lemma *Graph4*:

$\llbracket T \in \text{Reach } E; \text{Roots} \subseteq \text{Blacks } M; I \leq \text{length } E; T < \text{length } M; R < \text{length } E;$
 $\forall i < I. \neg \text{BtoW}(E!i, M); R < I; M!fst(E!R) = \text{Black}; M!T \neq \text{Black} \rrbracket \implies$
 $(\exists r. I \leq r \wedge r < \text{length } E \wedge \text{BtoW}(E[R := (fst(E!R), T)]!r, M))$
<proof>

declare *min.absorb1* [*simp del*] *min.absorb2* [*simp del*]

Graph 5

lemma *Graph5*:

$\llbracket T \in \text{Reach } E; \text{Roots} \subseteq \text{Blacks } M; \forall i < R. \neg \text{BtoW}(E!i, M); T < \text{length } M;$
 $R < \text{length } E; M!fst(E!R) = \text{Black}; M!snd(E!R) = \text{Black}; M!T \neq \text{Black} \rrbracket$
 $\implies (\exists r. R < r \wedge r < \text{length } E \wedge \text{BtoW}(E[R := (fst(E!R), T)]!r, M))$
<proof>

Other lemmas about graphs

lemma *Graph6*:

$\llbracket \text{Proper-Edges}(M, E); R < \text{length } E; T < \text{length } M \rrbracket \implies \text{Proper-Edges}(M, E[R := (fst(E!R), T)])$
<proof>

lemma *Graph7*:

$\llbracket \text{Proper-Edges}(M, E) \rrbracket \implies \text{Proper-Edges}(M[T := a], E)$
<proof>

lemma *Graph8*:

$\llbracket \text{Proper-Roots}(M) \rrbracket \implies \text{Proper-Roots}(M[T := a])$
<proof>

Some specific lemmata for the verification of garbage collection algorithms.

lemma *Graph9*: $j < \text{length } M \implies \text{Blacks } M \subseteq \text{Blacks } (M[j := \text{Black}])$
<proof>

lemma *Graph10* [*rule-format (no-asm)*]: $\forall i. M!i = a \longrightarrow M[i := a] = M$
<proof>

lemma *Graph11* [*rule-format (no-asm)*]:

$\llbracket M!j \neq \text{Black}; j < \text{length } M \rrbracket \implies \text{Blacks } M \subset \text{Blacks } (M[j := \text{Black}])$
<proof>

lemma *Graph12*: $\llbracket a \subseteq \text{Blacks } M; j < \text{length } M \rrbracket \implies a \subseteq \text{Blacks } (M[j := \text{Black}])$
<proof>

lemma *Graph13*: $\llbracket a \subset \text{Blacks } M; j < \text{length } M \rrbracket \implies a \subset \text{Blacks } (M[j := \text{Black}])$
<proof>

declare *Graph-defs* [*simp del*]

end

2.2 The Single Mutator Case

theory *Gar-Coll* **imports** *Graph OG-Syntax* **begin**

declare *psubsetE* [*rule del*]

Declaration of variables:

record *gar-coll-state* =
 M :: *nodes*
 E :: *edges*
 bc :: *nat set*
 obc :: *nat set*
 Ma :: *nodes*
 ind :: *nat*
 k :: *nat*
 z :: *bool*

2.2.1 The Mutator

The mutator first redirects an arbitrary edge R from an arbitrary accessible node towards an arbitrary accessible node T . It then colors the new target T black.

We declare the arbitrarily selected node and edge as constants:

consts $R :: nat$ $T :: nat$

The following predicate states, given a list of nodes m and a list of edges e , the conditions under which the selected edge R and node T are valid:

definition *Mut-init* :: *gar-coll-state* \Rightarrow *bool* **where**
 Mut-init \equiv « $T \in Reach \ 'E \wedge R < length \ 'E \wedge T < length \ 'M$ »

For the mutator we consider two modules, one for each action. An auxiliary variable $'z$ is set to false if the mutator has already redirected an edge but has not yet colored the new target.

definition *Redirect-Edge* :: *gar-coll-state ann-com* **where**
 Redirect-Edge \equiv $\{ \ 'Mut-init \wedge \ 'z \} \langle \ 'E := \ 'E[R := (fst(\ 'E!R), T)], \ 'z := (\neg \ 'z) \rangle$

definition *Color-Target* :: *gar-coll-state ann-com* **where**
 Color-Target \equiv $\{ \ 'Mut-init \wedge \neg \ 'z \} \langle \ 'M := \ 'M[T := Black], \ 'z := (\neg \ 'z) \rangle$

definition *Mutator* :: *gar-coll-state ann-com* **where**
 Mutator \equiv
 $\{ \ 'Mut-init \wedge \ 'z \}$
 WHILE *True* *INV* $\{ \ 'Mut-init \wedge \ 'z \}$
 DO *Redirect-Edge* ;; *Color-Target* *OD*

Correctness of the mutator

lemmas *mutator-defs* = *Mut-init-def Redirect-Edge-def Color-Target-def*

lemma *Redirect-Edge*:

⊢ *Redirect-Edge* *pre*(*Color-Target*)

⟨*proof*⟩

lemma *Color-Target*:

⊢ *Color-Target* {*′Mut-init* ∧ *′z*}

⟨*proof*⟩

lemma *Mutator*:

⊢ *Mutator* {*False*}

⟨*proof*⟩

2.2.2 The Collector

A constant *M-init* is used to give *′Ma* a suitable first value, defined as a list of nodes where only the *Roots* are black.

consts *M-init* :: *nodes*

definition *Proper-M-init* :: *gar-coll-state* ⇒ *bool* **where**

Proper-M-init ≡ « *Blacks* *M-init=Roots* ∧ *length* *M-init=length* *′M* »

definition *Proper* :: *gar-coll-state* ⇒ *bool* **where**

Proper ≡ « *Proper-Roots* *′M* ∧ *Proper-Edges*(*′M*, *′E*) ∧ *′Proper-M-init* »

definition *Safe* :: *gar-coll-state* ⇒ *bool* **where**

Safe ≡ « *Reach* *′E* ⊆ *Blacks* *′M* »

lemmas *collector-defs* = *Proper-M-init-def Proper-def Safe-def*

Blackening the roots

definition *Blacken-Roots* :: *gar-coll-state* *ann-com* **where**

Blacken-Roots ≡

{*′Proper*}

′ind:=0;;

{*′Proper* ∧ *′ind=0*}

WHILE *′ind<length* *′M*

INV {*′Proper* ∧ (∀ *i<′ind*. *i* ∈ *Roots* → *′M!**i=Black*) ∧ *′ind≤length* *′M*}

DO {*′Proper* ∧ (∀ *i<′ind*. *i* ∈ *Roots* → *′M!**i=Black*) ∧ *′ind<length* *′M*}

IF *′ind∈Roots* *THEN*

{*′Proper* ∧ (∀ *i<′ind*. *i* ∈ *Roots* → *′M!**i=Black*) ∧ *′ind<length* *′M* ∧

′ind∈Roots}

′M:=′M[*′ind:=Black*] *FI*;;

{*′Proper* ∧ (∀ *i<′ind+1*. *i* ∈ *Roots* → *′M!**i=Black*) ∧ *′ind<length* *′M*}

′ind:=′ind+1

OD

lemma *Blacken-Roots*:

$\vdash \text{Blacken-Roots } \{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \}\}$
 $\langle \text{proof} \rangle$

Propagating black

definition *PBInv* :: *gar-coll-state* \Rightarrow *nat* \Rightarrow *bool* **where**

$\text{PBInv} \equiv \ll \lambda \text{ind. } 'obc < \text{Blacks } 'M \vee (\forall i < \text{ind. } \neg \text{BtoW}('E!i, 'M) \vee$
 $(\neg 'z \wedge i = R \wedge (\text{snd}('E!R)) = T \wedge (\exists r. \text{ind} \leq r \wedge r < \text{length } 'E \wedge \text{BtoW}('E!r, 'M)))) \gg$

definition *Propagate-Black-aux* :: *gar-coll-state* *ann-com* **where**

$\text{Propagate-Black-aux} \equiv$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M \}\}$
 $'ind := 0;;$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M \wedge 'ind = 0 \}\}$
 $\text{WHILE } 'ind < \text{length } 'E$
 $\text{INV } \{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge 'PBInv 'ind \wedge 'ind \leq \text{length } 'E \}\}$
 $\text{DO } \{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge 'PBInv 'ind \wedge 'ind < \text{length } 'E \}\}$
 $\text{IF } 'M!(\text{fst}('E!'ind)) = \text{Black} \text{ THEN}$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge 'PBInv 'ind \wedge 'ind < \text{length } 'E \wedge 'M!\text{fst}('E!'ind) = \text{Black} \}\}$
 $'M := 'M[\text{snd}('E!'ind) := \text{Black}];;$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge 'PBInv ('ind + 1) \wedge 'ind < \text{length } 'E \}\}$
 $'ind := 'ind + 1$
 FI
 OD

lemma *Propagate-Black-aux*:

$\vdash \text{Propagate-Black-aux}$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge ('obc < \text{Blacks } 'M \vee 'Safe) \}\}$
 $\langle \text{proof} \rangle$

Refining propagating black

definition *Auxk* :: *gar-coll-state* \Rightarrow *bool* **where**

$\text{Auxk} \equiv \ll 'k < \text{length } 'M \wedge ('M!'k \neq \text{Black} \vee \neg \text{BtoW}('E!'ind, 'M) \vee$
 $'obc < \text{Blacks } 'M \vee (\neg 'z \wedge 'ind = R \wedge \text{snd}('E!R) = T$
 $\wedge (\exists r. 'ind < r \wedge r < \text{length } 'E \wedge \text{BtoW}('E!r, 'M))) \gg$

definition *Propagate-Black* :: *gar-coll-state* *ann-com* **where**

$\text{Propagate-Black} \equiv$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M \}\}$
 $'ind := 0;;$
 $\{\{ \text{Proper} \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M \wedge 'ind = 0 \}\}$

```

WHILE 'ind < length 'E
  INV { 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
        ∧ 'PBIInv 'ind ∧ 'ind ≤ length 'E }
  DO { 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
        ∧ 'PBIInv 'ind ∧ 'ind < length 'E }
  IF ('M!(fst ('E!'ind))) = Black THEN
    { 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
      ∧ 'PBIInv 'ind ∧ 'ind < length 'E ∧ ('M!(fst ('E!'ind))) = Black }
    'k := (snd ('E!'ind));
    { 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
      ∧ 'PBIInv 'ind ∧ 'ind < length 'E ∧ ('M!(fst ('E!'ind))) = Black
      ∧ 'Auxk }
    ⟨ 'M := 'M['k := Black],, 'ind := 'ind + 1 ⟩
  ELSE { 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
        ∧ 'PBIInv 'ind ∧ 'ind < length 'E }
    ⟨ IF ('M!(fst ('E!'ind))) ≠ Black THEN 'ind := 'ind + 1 FI ⟩
  FI
OD

```

lemma *Propagate-Black*:

```

⊢ Propagate-Black
{ 'Proper ∧ Roots ⊆ Blacks 'M ∧ 'obc ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
  ∧ ('obc < Blacks 'M ∨ 'Safe) }
⟨ proof ⟩

```

Counting black nodes

definition *CountInv* :: *gar-coll-state* ⇒ *nat* ⇒ *bool* **where**

CountInv ≡ « λ*ind*. {*i*. *i* < *ind* ∧ 'M*i* = Black } ⊆ 'bc »

definition *Count* :: *gar-coll-state* *ann-com* **where**

```

Count ≡
{ 'Proper ∧ Roots ⊆ Blacks 'M
  ∧ 'obc ⊆ Blacks 'Ma ∧ Blacks 'Ma ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
  ∧ length 'Ma = length 'M ∧ ('obc < Blacks 'Ma ∨ 'Safe) ∧ 'bc = {} }
'ind := 0;;
{ 'Proper ∧ Roots ⊆ Blacks 'M
  ∧ 'obc ⊆ Blacks 'Ma ∧ Blacks 'Ma ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
  ∧ length 'Ma = length 'M ∧ ('obc < Blacks 'Ma ∨ 'Safe) ∧ 'bc = {}
  ∧ 'ind = 0 }
WHILE 'ind < length 'M
  INV { 'Proper ∧ Roots ⊆ Blacks 'M
        ∧ 'obc ⊆ Blacks 'Ma ∧ Blacks 'Ma ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
        ∧ length 'Ma = length 'M ∧ 'CountInv 'ind
        ∧ ('obc < Blacks 'Ma ∨ 'Safe) ∧ 'ind ≤ length 'M }
  DO { 'Proper ∧ Roots ⊆ Blacks 'M
        ∧ 'obc ⊆ Blacks 'Ma ∧ Blacks 'Ma ⊆ Blacks 'M ∧ 'bc ⊆ Blacks 'M
        ∧ length 'Ma = length 'M ∧ 'CountInv 'ind
        ∧ ('obc < Blacks 'Ma ∨ 'Safe) ∧ 'ind < length 'M }

```

IF $'M!ind=Black$
 THEN $\{ 'Proper \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma=length 'M \wedge 'CountInv 'ind$
 $\wedge ('obc < Blacks 'Ma \vee 'Safe) \wedge 'ind < length 'M \wedge 'M!ind=Black \}$
 $'bc:=insert 'ind 'bc$
 FI;;
 $\{ 'Proper \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma=length 'M \wedge 'CountInv ('ind+1)$
 $\wedge ('obc < Blacks 'Ma \vee 'Safe) \wedge 'ind < length 'M \}$
 $'ind:='ind+1$
 OD

lemma Count:

$\vdash Count$
 $\{ 'Proper \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq 'bc \wedge 'bc \subseteq Blacks 'M \wedge length 'Ma=length$
 $'M$
 $\wedge ('obc < Blacks 'Ma \vee 'Safe) \}$
 <proof>

Appending garbage nodes to the free list

axiomatization *Append-to-free* :: $nat \times edges \Rightarrow edges$

where

Append-to-free0: $length (Append-to-free (i, e)) = length e$ **and**
Append-to-free1: *Proper-Edges* (m, e)
 $\implies Proper-Edges (m, Append-to-free(i, e))$ **and**
Append-to-free2: $i \notin Reach e$
 $\implies n \in Reach (Append-to-free(i, e)) = (n = i \vee n \in Reach e)$

definition *AppendInv* :: $gar-coll-state \Rightarrow nat \Rightarrow bool$ **where**

AppendInv $\equiv \llbracket \lambda ind. \forall i < length 'M. ind \leq i \longrightarrow i \in Reach 'E \longrightarrow 'M!i=Black \rrbracket$

definition *Append* :: $gar-coll-state \text{ ann-com}$ **where**

Append \equiv
 $\{ 'Proper \wedge Roots \subseteq Blacks 'M \wedge 'Safe \}$
 $'ind:=0;$
 $\{ 'Proper \wedge Roots \subseteq Blacks 'M \wedge 'Safe \wedge 'ind=0 \}$
 WHILE $'ind < length 'M$
 INV $\{ 'Proper \wedge 'AppendInv 'ind \wedge 'ind \leq length 'M \}$
 DO $\{ 'Proper \wedge 'AppendInv 'ind \wedge 'ind < length 'M \}$
 IF $'M!ind=Black$ THEN
 $\{ 'Proper \wedge 'AppendInv 'ind \wedge 'ind < length 'M \wedge 'M!ind=Black \}$
 $'M:='M['ind:=White]$
 ELSE $\{ 'Proper \wedge 'AppendInv 'ind \wedge 'ind < length 'M \wedge 'ind \notin Reach 'E \}$
 $'E:=Append-to-free('ind, 'E)$
 FI;;

$$\{\text{' } Proper \wedge \text{' AppendInv } (' ind+1) \wedge \text{' } ind < \text{length } \text{' } M\}$$

$$\text{' } ind := \text{' } ind + 1$$

OD

lemma *Append*:
 $\vdash \text{Append } \{\text{' } Proper\}$
 ⟨proof⟩

Correctness of the Collector

definition *Collector* :: *gar-coll-state ann-com where*
Collector \equiv
 $\{\text{' } Proper\}$
 WHILE True INV $\{\text{' } Proper\}$
 DO
 Blacken-Roots;;
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M\}$
 $\text{' } obc := \{\};$
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } obc = \{\}\}$
 $\text{' } bc := \text{Roots};$
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } obc = \{\} \wedge \text{' } bc = \text{Roots}\}$
 $\text{' } Ma := M\text{-init};$
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } obc = \{\} \wedge \text{' } bc = \text{Roots} \wedge \text{' } Ma = M\text{-init}\}$
 WHILE $\text{' } obc \neq \text{' } bc$
 INV $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M$
 $\wedge \text{' } obc \subseteq \text{Blacks } \text{' } Ma \wedge \text{Blacks } \text{' } Ma \subseteq \text{' } bc \wedge \text{' } bc \subseteq \text{Blacks } \text{' } M$
 $\wedge \text{length } \text{' } Ma = \text{length } \text{' } M \wedge (\text{' } obc < \text{Blacks } \text{' } Ma \vee \text{' } Safe)\}$
 DO $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } bc \subseteq \text{Blacks } \text{' } M\}$
 $\text{' } obc := \text{' } bc;$
 Propagate-Black;;
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } obc \subseteq \text{Blacks } \text{' } M \wedge \text{' } bc \subseteq \text{Blacks } \text{' } M$
 $\wedge (\text{' } obc < \text{Blacks } \text{' } M \vee \text{' } Safe)\}$
 $\text{' } Ma := \text{' } M;$
 $\{\text{' } Proper \wedge \text{Roots} \subseteq \text{Blacks } \text{' } M \wedge \text{' } obc \subseteq \text{Blacks } \text{' } Ma$
 $\wedge \text{Blacks } \text{' } Ma \subseteq \text{Blacks } \text{' } M \wedge \text{' } bc \subseteq \text{Blacks } \text{' } M \wedge \text{length } \text{' } Ma = \text{length } \text{' } M$
 $\wedge (\text{' } obc < \text{Blacks } \text{' } Ma \vee \text{' } Safe)\}$
 $\text{' } bc := \{\};$
 Count
 OD;;
 Append
 OD

lemma *Collector*:
 $\vdash \text{Collector } \{\text{False}\}$
 ⟨proof⟩

2.2.3 Interference Freedom

lemmas *modules = Redirect-Edge-def Color-Target-def Blacken-Roots-def*
Propagate-Black-def Count-def Append-def

lemmas *Invariants* = *PBInv-def Auxk-def CountInv-def AppendInv-def*
lemmas *abbrev* = *collector-defs mutator-defs Invariants*

lemma *interfree-Blacken-Roots-Redirect-Edge*:
interfree-aux (*Some Blacken-Roots*, {}, *Some Redirect-Edge*)
<proof>

lemma *interfree-Redirect-Edge-Blacken-Roots*:
interfree-aux (*Some Redirect-Edge*, {}, *Some Blacken-Roots*)
<proof>

lemma *interfree-Blacken-Roots-Color-Target*:
interfree-aux (*Some Blacken-Roots*, {}, *Some Color-Target*)
<proof>

lemma *interfree-Color-Target-Blacken-Roots*:
interfree-aux (*Some Color-Target*, {}, *Some Blacken-Roots*)
<proof>

lemma *interfree-Propagate-Black-Redirect-Edge*:
interfree-aux (*Some Propagate-Black*, {}, *Some Redirect-Edge*)
<proof>

lemma *interfree-Redirect-Edge-Propagate-Black*:
interfree-aux (*Some Redirect-Edge*, {}, *Some Propagate-Black*)
<proof>

lemma *interfree-Propagate-Black-Color-Target*:
interfree-aux (*Some Propagate-Black*, {}, *Some Color-Target*)
<proof>

lemma *interfree-Color-Target-Propagate-Black*:
interfree-aux (*Some Color-Target*, {}, *Some Propagate-Black*)
<proof>

lemma *interfree-Count-Redirect-Edge*:
interfree-aux (*Some Count*, {}, *Some Redirect-Edge*)
<proof>

lemma *interfree-Redirect-Edge-Count*:
interfree-aux (*Some Redirect-Edge*, {}, *Some Count*)
<proof>

lemma *interfree-Count-Color-Target*:
interfree-aux (*Some Count*, {}, *Some Color-Target*)
<proof>

lemma *interfree-Color-Target-Count*:
interfree-aux (*Some Color-Target*, {}, *Some Count*)

<proof>

lemma *interfree-Append-Redirect-Edge:*

interfree-aux (Some Append, {}, Some Redirect-Edge)

<proof>

lemma *interfree-Redirect-Edge-Append:*

interfree-aux (Some Redirect-Edge, {}, Some Append)

<proof>

lemma *interfree-Append-Color-Target:*

interfree-aux (Some Append, {}, Some Color-Target)

<proof>

lemma *interfree-Color-Target-Append:*

interfree-aux (Some Color-Target, {}, Some Append)

<proof>

lemmas *collector-mutator-interfree =*

interfree-Blacken-Roots-Redirect-Edge interfree-Blacken-Roots-Color-Target
interfree-Propagate-Black-Redirect-Edge interfree-Propagate-Black-Color-Target
interfree-Count-Redirect-Edge interfree-Count-Color-Target
interfree-Append-Redirect-Edge interfree-Append-Color-Target
interfree-Redirect-Edge-Blacken-Roots interfree-Color-Target-Blacken-Roots
interfree-Redirect-Edge-Propagate-Black interfree-Color-Target-Propagate-Black
interfree-Redirect-Edge-Count interfree-Color-Target-Count
interfree-Redirect-Edge-Append interfree-Color-Target-Append

Interference freedom Collector-Mutator

lemma *interfree-Collector-Mutator:*

interfree-aux (Some Collector, {}, Some Mutator)

<proof>

Interference freedom Mutator-Collector

lemma *interfree-Mutator-Collector:*

interfree-aux (Some Mutator, {}, Some Collector)

<proof>

The Garbage Collection algorithm

In total there are 289 verification conditions.

lemma *Gar-Coll:*

$\| - \{ \text{Proper} \wedge \text{Mut-init} \wedge \text{z} \}$

COBEGIN

Collector

$\{ \text{False} \}$

$\|$

```

    Mutator
  {False}
COEND
  {False}
<proof>

```

end

2.3 The Multi-Mutator Case

theory *Mul-Gar-Coll* **imports** *Graph OG-Syntax* **begin**

The full theory takes aprox. 18 minutes.

```

record mut =
  Z :: bool
  R :: nat
  T :: nat

```

Declaration of variables:

```

record mul-gar-coll-state =
  M :: nodes
  E :: edges
  bc :: nat set
  obc :: nat set
  Ma :: nodes
  ind :: nat
  k :: nat
  q :: nat
  l :: nat
  Muts :: mut list

```

2.3.1 The Mutators

definition *Mul-mut-init* :: *mul-gar-coll-state* \Rightarrow *nat* \Rightarrow *bool* **where**

$$\begin{aligned} \text{Mul-mut-init} \equiv \ll \lambda n. n = \text{length } 'Muts \wedge (\forall i < n. R ('Muts!i) < \text{length } 'E \\ \wedge T ('Muts!i) < \text{length } 'M) \gg \end{aligned}$$

definition *Mul-Redirect-Edge* *j n* :: *nat* \Rightarrow *nat* \Rightarrow *mul-gar-coll-state* *ann-com* **where**

$$\begin{aligned} \text{Mul-Redirect-Edge } j \ n \equiv \\ \{ 'Mul-mut-init \ n \ \wedge \ Z ('Muts!j) \} \\ \langle \text{IF } T ('Muts!j) \in \text{Reach } 'E \ \text{THEN} \\ 'E := 'E[R ('Muts!j) := (fst ('E!R ('Muts!j))), T ('Muts!j))] \ \text{FI}, \\ 'Muts := 'Muts[j := ('Muts!j)] \ (Z := \text{False}) \rangle \end{aligned}$$

definition *Mul-Color-Target* *j n* :: *nat* \Rightarrow *nat* \Rightarrow *mul-gar-coll-state* *ann-com* **where**

$$\begin{aligned} \text{Mul-Color-Target } j \ n \equiv \\ \{ 'Mul-mut-init \ n \ \wedge \ \neg \ Z ('Muts!j) \} \\ \langle 'M := 'M[T ('Muts!j) := \text{Black}], 'Muts := 'Muts[j := ('Muts!j)] \ (Z := \text{True}) \rangle \end{aligned}$$

definition *Mul-Mutator* :: nat \Rightarrow nat \Rightarrow mul-gar-coll-state ann-com **where**

Mul-Mutator *j n* \equiv
 $\{\! \{ \text{Mul-mut-init } n \wedge Z (\text{Muts!}j) \} \!\}$
 WHILE True
 INV $\{\! \{ \text{Mul-mut-init } n \wedge Z (\text{Muts!}j) \} \!\}$
 DO *Mul-Redirect-Edge* *j n* ;;
Mul-Color-Target *j n*
 OD

lemmas *mul-mutator-defs* = *Mul-mut-init-def* *Mul-Redirect-Edge-def* *Mul-Color-Target-def*

Correctness of the proof outline of one mutator

lemma *Mul-Redirect-Edge*: $0 \leq j \wedge j < n \implies$

\vdash *Mul-Redirect-Edge* *j n*
 $\text{pre}(\text{Mul-Color-Target } j n)$
 $\langle \text{proof} \rangle$

lemma *Mul-Color-Target*: $0 \leq j \wedge j < n \implies$

\vdash *Mul-Color-Target* *j n*
 $\{\! \{ \text{Mul-mut-init } n \wedge Z (\text{Muts!}j) \} \!\}$
 $\langle \text{proof} \rangle$

lemma *Mul-Mutator*: $0 \leq j \wedge j < n \implies$

\vdash *Mul-Mutator* *j n* $\{\! \{ \text{False} \} \!\}$
 $\langle \text{proof} \rangle$

Interference freedom between mutators

lemma *Mul-interfree-Redirect-Edge-Redirect-Edge*:

$\llbracket 0 \leq i; i < n; 0 \leq j; j < n; i \neq j \rrbracket \implies$
 $\text{interfree-aux } (\text{Some } (\text{Mul-Redirect-Edge } i n), \{\}, \text{Some}(\text{Mul-Redirect-Edge } j n))$
 $\langle \text{proof} \rangle$

lemma *Mul-interfree-Redirect-Edge-Color-Target*:

$\llbracket 0 \leq i; i < n; 0 \leq j; j < n; i \neq j \rrbracket \implies$
 $\text{interfree-aux } (\text{Some}(\text{Mul-Redirect-Edge } i n), \{\}, \text{Some}(\text{Mul-Color-Target } j n))$
 $\langle \text{proof} \rangle$

lemma *Mul-interfree-Color-Target-Redirect-Edge*:

$\llbracket 0 \leq i; i < n; 0 \leq j; j < n; i \neq j \rrbracket \implies$
 $\text{interfree-aux } (\text{Some}(\text{Mul-Color-Target } i n), \{\}, \text{Some}(\text{Mul-Redirect-Edge } j n))$
 $\langle \text{proof} \rangle$

lemma *Mul-interfree-Color-Target-Color-Target*:

$\llbracket 0 \leq i; i < n; 0 \leq j; j < n; i \neq j \rrbracket \implies$
 $\text{interfree-aux } (\text{Some}(\text{Mul-Color-Target } i n), \{\}, \text{Some}(\text{Mul-Color-Target } j n))$
 $\langle \text{proof} \rangle$

lemmas *mul-mutator-interfree* =
Mul-interfree-Redirect-Edge-Redirect-Edge Mul-interfree-Redirect-Edge-Color-Target
Mul-interfree-Color-Target-Redirect-Edge Mul-interfree-Color-Target-Color-Target

lemma *Mul-interfree-Mutator-Mutator*: $[[i < n; j < n; i \neq j]] \implies$
interfree-aux (*Some* (*Mul-Mutator* *i n*), {}, *Some* (*Mul-Mutator* *j n*))
 ⟨*proof*⟩

Modular Parameterized Mutators

lemma *Mul-Parameterized-Mutators*: $0 < n \implies$
 ||– {*Mul-mut-init* *n* \wedge ($\forall i < n. Z$ (*Muts!**i*))}
 COBEGIN
 SCHEME [$0 \leq j < n$]
Mul-Mutator *j n*
 {*False*}
 COEND
 {*False*}
 ⟨*proof*⟩

2.3.2 The Collector

definition *Queue* :: *mul-gar-coll-state* \Rightarrow *nat* **where**
Queue \equiv « *length* (*filter* ($\lambda i. \neg Z$ *i* \wedge *M!*(*T* *i*) \neq *Black*) *Muts*) »

consts *M-init* :: *nodes*

definition *Proper-M-init* :: *mul-gar-coll-state* \Rightarrow *bool* **where**
Proper-M-init \equiv « *Blacks* *M-init* = *Roots* \wedge *length* *M-init* = *length* *M* »

definition *Mul-Proper* :: *mul-gar-coll-state* \Rightarrow *nat* \Rightarrow *bool* **where**
Mul-Proper \equiv « $\lambda n. Proper-Roots$ *M* \wedge *Proper-Edges* (*M*, *E*) \wedge *Proper-M-init*
 \wedge *n* = *length* *Muts* »

definition *Safe* :: *mul-gar-coll-state* \Rightarrow *bool* **where**
Safe \equiv « *Reach* *E* \subseteq *Blacks* *M* »

lemmas *mul-collector-defs* = *Proper-M-init-def Mul-Proper-def Safe-def*

Blackening Roots

definition *Mul-Blacken-Roots* :: *nat* \Rightarrow *mul-gar-coll-state* *ann-com* **where**
Mul-Blacken-Roots *n* \equiv
 {*Mul-Proper* *n*}
ind := 0;;
 {*Mul-Proper* *n* \wedge *ind* = 0}
 WHILE *ind* < *length* *M*
 INV {*Mul-Proper* *n* \wedge ($\forall i < ind. i \in Roots \implies M!i = Black$) \wedge *ind* \leq *length*
M}
 DO {*Mul-Proper* *n* \wedge ($\forall i < ind. i \in Roots \implies M!i = Black$) \wedge *ind* < *length* *M*}

IF $'ind \in \text{Roots}$ THEN
 $\{ \text{'Mul-Prop} n \wedge (\forall i < 'ind. i \in \text{Roots} \longrightarrow 'M!i = \text{Black}) \wedge 'ind < \text{length } 'M \wedge 'ind \in \text{Roots} \}$
 $'M := 'M['ind := \text{Black}]$ FI;;
 $\{ \text{'Mul-Prop} n \wedge (\forall i < 'ind + 1. i \in \text{Roots} \longrightarrow 'M!i = \text{Black}) \wedge 'ind < \text{length } 'M \}$
 $'ind := 'ind + 1$
 OD

lemma *Mul-Blacken-Roots*:

$\vdash \text{Mul-Blacken-Roots } n$
 $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M \}$
<proof>

Propagating Black

definition *Mul-PBInv* :: *mul-gar-coll-state* \Rightarrow *bool* **where**

$\text{Mul-PBInv} \equiv \ll 'Safe \vee 'obc \subseteq \text{Blacks } 'M \vee 'l < 'Queue$
 $\vee (\forall i < 'ind. \neg \text{BtoW}('E!i, 'M)) \wedge 'l \leq 'Queue \gg$

definition *Mul-Auxk* :: *mul-gar-coll-state* \Rightarrow *bool* **where**

$\text{Mul-Auxk} \equiv \ll 'l < 'Queue \vee 'M!k \neq \text{Black} \vee \neg \text{BtoW}('E! 'ind, 'M) \vee 'obc \subseteq \text{Blacks } 'M \gg$

definition *Mul-Propagate-Black* :: *nat* \Rightarrow *mul-gar-coll-state* *ann-com* **where**

$\text{Mul-Propagate-Black } n \equiv$
 $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge ('Safe \vee 'l \leq 'Queue \vee 'obc \subseteq \text{Blacks } 'M) \}$
 $'ind := 0;$
 $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M$
 $\wedge 'obc \subseteq \text{Blacks } 'M \wedge \text{Blacks } 'M \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge ('Safe \vee 'l \leq 'Queue \vee 'obc \subseteq \text{Blacks } 'M) \wedge 'ind = 0 \}$
WHILE $'ind < \text{length } 'E$
INV $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M$
 $\wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge \text{Mul-PBInv} \wedge 'ind \leq \text{length } 'E \}$
DO $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M$
 $\wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge \text{Mul-PBInv} \wedge 'ind < \text{length } 'E \}$
IF $'M!(\text{fst } ('E! 'ind)) = \text{Black}$ **THEN**
 $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M$
 $\wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge \text{Mul-PBInv} \wedge ('M! \text{fst}('E! 'ind)) = \text{Black} \wedge 'ind < \text{length } 'E \}$
 $'k := \text{snd}('E! 'ind);;$
 $\{ \text{'Mul-Prop} n \wedge \text{Roots} \subseteq \text{Blacks } 'M$
 $\wedge 'obc \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$
 $\wedge ('Safe \vee 'obc \subseteq \text{Blacks } 'M \vee 'l < 'Queue \vee (\forall i < 'ind. \neg \text{BtoW}('E!i, 'M))$
 $\wedge 'l \leq 'Queue \wedge \text{Mul-Auxk}) \wedge 'k < \text{length } 'M \wedge 'M! \text{fst}('E! 'ind) = \text{Black}$
 $\wedge 'ind < \text{length } 'E \}$

$\langle 'M := 'M['k := Black], 'ind := 'ind + 1 \rangle$
ELSE $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge 'Mul-PBInv \wedge 'ind < length 'E \}$
 $\langle IF 'M!(fst('E!ind)) \neq Black THEN 'ind := 'ind + 1 FI \rangle FI$
OD

lemma *Mul-Propagate-Black:*

$\vdash Mul-Propagate-Black\ n$
 $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M \wedge 'obc \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'M \vee 'l < 'Queue \wedge ('l \leq 'Queue \vee 'obc \subseteq Blacks$
 $'M)) \}$
<proof>

Counting Black Nodes

definition *Mul-CountInv* :: *mul-gar-coll-state* \Rightarrow *nat* \Rightarrow *bool* **where**

Mul-CountInv \equiv « $\lambda ind. \{ i. i < ind \wedge 'Ma!i = Black \} \subseteq 'bc$ »

definition *Mul-Count* :: *nat* \Rightarrow *mul-gar-coll-state ann-com* **where**

Mul-Count $n \equiv$
 $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n + 1 \wedge 'bc = \{ \} \}$
 $'ind := 0;$
 $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n + 1 \wedge 'bc = \{ \} \wedge 'ind = 0 \}$
WHILE $'ind < length 'M$
INV $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M \wedge 'Mul-CountInv 'ind$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n + 1 \wedge 'ind \leq length 'M \}$
DO $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M \wedge 'Mul-CountInv 'ind$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n + 1 \wedge 'ind < length 'M \}$
IF $'M! 'ind = Black$
THEN $\{ \{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M \wedge 'Mul-CountInv 'ind$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks$
 $'M))$

$$\wedge 'q < n+1 \wedge 'ind < \text{length } 'M \wedge 'M!'ind = \text{Black}\}$$

$$'bc := \text{insert } 'ind \ 'bc$$

FI;;

$$\{\{ 'Mul-Prop\text{er } n \wedge \text{Roots} \subseteq \text{Blacks } 'M$$

$$\wedge 'obc \subseteq \text{Blacks } 'Ma \wedge \text{Blacks } 'Ma \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$$

$$\wedge \text{length } 'Ma = \text{length } 'M \wedge 'Mul-CountInv ('ind+1)$$

$$\wedge ('Safe \vee 'obc \subseteq \text{Blacks } 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq \text{Blacks } 'M))$$

$$\wedge 'q < n+1 \wedge 'ind < \text{length } 'M\}$$

$$'ind := 'ind+1$$

OD

lemma *Mul-Count*:

$$\vdash \text{Mul-Count } n$$

$$\{\{ 'Mul-Prop\text{er } n \wedge \text{Roots} \subseteq \text{Blacks } 'M$$

$$\wedge 'obc \subseteq \text{Blacks } 'Ma \wedge \text{Blacks } 'Ma \subseteq \text{Blacks } 'M \wedge 'bc \subseteq \text{Blacks } 'M$$

$$\wedge \text{length } 'Ma = \text{length } 'M \wedge \text{Blacks } 'Ma \subseteq 'bc$$

$$\wedge ('Safe \vee 'obc \subseteq \text{Blacks } 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq \text{Blacks } 'M))$$

$$\wedge 'q < n+1\}$$

<proof>

Appending garbage nodes to the free list

axiomatization *Append-to-free* :: $\text{nat} \times \text{edges} \Rightarrow \text{edges}$

where

Append-to-free0: $\text{length } (\text{Append-to-free } (i, e)) = \text{length } e$ **and**
Append-to-free1: *Proper-Edges* (m, e)
 $\implies \text{Proper-Edges } (m, \text{Append-to-free}(i, e))$ **and**
Append-to-free2: $i \notin \text{Reach } e$
 $\implies n \in \text{Reach } (\text{Append-to-free}(i, e)) = (n = i \vee n \in \text{Reach } e)$

definition *Mul-AppendInv* :: $\text{mul-gar-coll-state} \Rightarrow \text{nat} \Rightarrow \text{bool}$ **where**

Mul-AppendInv $\equiv \ll \lambda ind. (\forall i. ind \leq i \longrightarrow i < \text{length } 'M \longrightarrow i \in \text{Reach } 'E \longrightarrow 'M!'i = \text{Black}) \gg$

definition *Mul-Append* :: $\text{nat} \Rightarrow \text{mul-gar-coll-state} \text{ ann-com}$ **where**

Mul-Append $n \equiv$
 $\{\{ 'Mul-Prop\text{er } n \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'Safe\}$
 $'ind := 0;$
 $\{\{ 'Mul-Prop\text{er } n \wedge \text{Roots} \subseteq \text{Blacks } 'M \wedge 'Safe \wedge 'ind = 0\}$
 $\text{WHILE } 'ind < \text{length } 'M$
 $\text{INV } \{\{ 'Mul-Prop\text{er } n \wedge 'Mul-AppendInv 'ind \wedge 'ind \leq \text{length } 'M\}$
 $\text{DO } \{\{ 'Mul-Prop\text{er } n \wedge 'Mul-AppendInv 'ind \wedge 'ind < \text{length } 'M\}$
 $\text{IF } 'M!'ind = \text{Black} \text{ THEN}$
 $\{\{ 'Mul-Prop\text{er } n \wedge 'Mul-AppendInv 'ind \wedge 'ind < \text{length } 'M \wedge 'M!'ind = \text{Black}\}$
 $'M := 'M['ind := \text{White}]$
 ELSE
 $\{\{ 'Mul-Prop\text{er } n \wedge 'Mul-AppendInv 'ind \wedge 'ind < \text{length } 'M \wedge 'ind \notin \text{Reach}$
 $'E\}$
 $'E := \text{Append-to-free}('ind, 'E)$

$FI;$
 $\{\{ 'Mul-Prop\text{-}n \wedge 'Mul-AppendInv ('ind+1) \wedge 'ind < length 'M \}$
 $'ind := 'ind+1$
 OD

lemma *Mul-Append*:
 $\vdash 'Mul-Append\ n$
 $\{\{ 'Mul-Prop\text{-}n \}$
 $\langle proof \rangle$

Collector

definition *Mul-Collector* :: $nat \Rightarrow mul\text{-}gar\text{-}coll\text{-}state\ ann\text{-}com$ **where**

$Mul-Collector\ n \equiv$
 $\{\{ 'Mul-Prop\text{-}n \}$
 $WHILE\ True\ INV\ \{\{ 'Mul-Prop\text{-}n \}$
 DO
 $Mul-Blacken-Roots\ n ;;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \}$
 $'obc := \{\};;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \wedge 'obc = \{\} \}$
 $'bc := Roots;;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \wedge 'obc = \{\} \wedge 'bc = Roots \}$
 $'l := 0;;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \wedge 'obc = \{\} \wedge 'bc = Roots \wedge 'l = 0 \}$
 $WHILE\ 'l < n+1$
 $INV\ \{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \wedge 'bc \subseteq Blacks\ 'M \wedge$
 $('Safe \vee ('l \leq 'Queue \vee 'bc \subseteq Blacks\ 'M) \wedge 'l < n+1) \}$
 $DO\ \{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M \wedge 'bc \subseteq Blacks\ 'M$
 $\wedge ('Safe \vee 'l \leq 'Queue \vee 'bc \subseteq Blacks\ 'M) \}$
 $'obc := 'bc;;$
 $Mul-Propagate-Black\ n;;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M$
 $\wedge 'obc \subseteq Blacks\ 'M \wedge 'bc \subseteq Blacks\ 'M$
 $\wedge ('Safe \vee 'obc \subseteq Blacks\ 'M \vee 'l < 'Queue$
 $\wedge ('l \leq 'Queue \vee 'obc \subseteq Blacks\ 'M) \}$
 $'bc := \{\};;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M$
 $\wedge 'obc \subseteq Blacks\ 'M \wedge 'bc \subseteq Blacks\ 'M$
 $\wedge ('Safe \vee 'obc \subseteq Blacks\ 'M \vee 'l < 'Queue$
 $\wedge ('l \leq 'Queue \vee 'obc \subseteq Blacks\ 'M) \wedge 'bc = \{\} \}$
 $\langle 'Ma := 'M,, 'q := 'Queue \rangle;;$
 $Mul-Count\ n;;$
 $\{\{ 'Mul-Prop\text{-}n \wedge Roots \subseteq Blacks\ 'M$
 $\wedge 'obc \subseteq Blacks\ 'Ma \wedge Blacks\ 'Ma \subseteq Blacks\ 'M \wedge 'bc \subseteq Blacks\ 'M$
 $\wedge length\ 'Ma = length\ 'M \wedge Blacks\ 'Ma \subseteq 'bc$
 $\wedge ('Safe \vee 'obc \subseteq Blacks\ 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks\ 'M))$
 $\wedge 'q < n+1 \}$
 $IF\ 'obc = 'bc\ THEN$

$\{\{ 'Mul-Prop\} n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M \wedge Blacks 'Ma \subseteq 'bc$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n+1 \wedge 'obc = 'bc\}$
 $'l := 'l+1$
ELSE $\{\{ 'Mul-Prop\} n \wedge Roots \subseteq Blacks 'M$
 $\wedge 'obc \subseteq Blacks 'Ma \wedge Blacks 'Ma \subseteq Blacks 'M \wedge 'bc \subseteq Blacks 'M$
 $\wedge length 'Ma = length 'M \wedge Blacks 'Ma \subseteq 'bc$
 $\wedge ('Safe \vee 'obc \subseteq Blacks 'Ma \vee 'l < 'q \wedge ('q \leq 'Queue \vee 'obc \subseteq Blacks 'M))$
 $\wedge 'q < n+1 \wedge 'obc \neq 'bc\}$
 $'l := 0 FI$
OD;;
Mul-Append n
OD

lemmas mul-modules = Mul-Redirect-Edge-def Mul-Color-Target-def
Mul-Blacken-Roots-def Mul-Propagate-Black-def
Mul-Count-def Mul-Append-def

lemma Mul-Collector:

$\vdash Mul-Collector n$
 $\{\{ False\}$
 $\langle proof \rangle$

2.3.3 Interference Freedom

lemma le-length-filter-update [rule-format]:

$\forall i. (\neg P (list!i) \vee P j) \wedge i < length list$
 $\longrightarrow length(filter P list) \leq length(filter P (list[i:=j]))$
 $\langle proof \rangle$

lemma less-length-filter-update [rule-format]:

$\forall i. P j \wedge \neg(P (list!i)) \wedge i < length list$
 $\longrightarrow length(filter P list) < length(filter P (list[i:=j]))$
 $\langle proof \rangle$

lemma Mul-interfree-Blacken-Roots-Redirect-Edge: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Blacken-Roots n), {}, Some(Mul-Redirect-Edge j n))
 $\langle proof \rangle$

lemma Mul-interfree-Redirect-Edge-Blacken-Roots: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Redirect-Edge j n), {}, Some(Mul-Blacken-Roots n))
 $\langle proof \rangle$

lemma Mul-interfree-Blacken-Roots-Color-Target: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Blacken-Roots n), {}, Some(Mul-Color-Target j n))
 $\langle proof \rangle$

lemma *Mul-interfree-Color-Target-Blacken-Roots*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Color-Target j n), {}, Some (Mul-Blacken-Roots n))
 ⟨proof⟩

lemma *Mul-interfree-Propagate-Black-Redirect-Edge*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Propagate-Black n), {}, Some (Mul-Redirect-Edge j n))
 ⟨proof⟩

lemma *Mul-interfree-Redirect-Edge-Propagate-Black*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Redirect-Edge j n), {}, Some (Mul-Propagate-Black n))
 ⟨proof⟩

lemma *Mul-interfree-Propagate-Black-Color-Target*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Propagate-Black n), {}, Some (Mul-Color-Target j n))
 ⟨proof⟩

lemma *Mul-interfree-Color-Target-Propagate-Black*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Color-Target j n), {}, Some(Mul-Propagate-Black n))
 ⟨proof⟩

lemma *Mul-interfree-Count-Redirect-Edge*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Count n), {}, Some(Mul-Redirect-Edge j n))
 ⟨proof⟩

lemma *Mul-interfree-Redirect-Edge-Count*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Redirect-Edge j n), {}, Some(Mul-Count n))
 ⟨proof⟩

lemma *Mul-interfree-Count-Color-Target*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Count n), {}, Some(Mul-Color-Target j n))
 ⟨proof⟩

lemma *Mul-interfree-Color-Target-Count*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Color-Target j n), {}, Some(Mul-Count n))
 ⟨proof⟩

lemma *Mul-interfree-Append-Redirect-Edge*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Append n), {}, Some(Mul-Redirect-Edge j n))
 ⟨proof⟩

lemma *Mul-interfree-Redirect-Edge-Append*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Redirect-Edge j n), {}, Some(Mul-Append n))
 ⟨proof⟩

lemma *Mul-interfree-Append-Color-Target*: $\llbracket 0 \leq j; j < n \rrbracket \implies$
interfree-aux (Some(Mul-Append n), {}, Some(Mul-Color-Target j n))
 ⟨proof⟩

lemma *Mul-interfree-Color-Target-Append*: $\llbracket 0 \leq j; j < n \rrbracket \implies$

interfree-aux (*Some*(*Mul-Color-Target* *j n*), {}, *Some*(*Mul-Append* *n*))
 ⟨*proof*⟩

Interference freedom Collector-Mutator

lemmas *mul-collector-mutator-interfree* =
Mul-interfree-Blacken-Roots-Redirect-Edge *Mul-interfree-Blacken-Roots-Color-Target*
Mul-interfree-Propagate-Black-Redirect-Edge *Mul-interfree-Propagate-Black-Color-Target*
Mul-interfree-Count-Redirect-Edge *Mul-interfree-Count-Color-Target*
Mul-interfree-Append-Redirect-Edge *Mul-interfree-Append-Color-Target*
Mul-interfree-Redirect-Edge-Blacken-Roots *Mul-interfree-Color-Target-Blacken-Roots*
Mul-interfree-Redirect-Edge-Propagate-Black *Mul-interfree-Color-Target-Propagate-Black*
Mul-interfree-Redirect-Edge-Count *Mul-interfree-Color-Target-Count*
Mul-interfree-Redirect-Edge-Append *Mul-interfree-Color-Target-Append*

lemma *Mul-interfree-Collector-Mutator*: $j < n \implies$
interfree-aux (*Some* (*Mul-Collector* *n*), {}, *Some* (*Mul-Mutator* *j n*))
 ⟨*proof*⟩

Interference freedom Mutator-Collector

lemma *Mul-interfree-Mutator-Collector*: $j < n \implies$
interfree-aux (*Some* (*Mul-Mutator* *j n*), {}, *Some* (*Mul-Collector* *n*))
 ⟨*proof*⟩

The Multi-Mutator Garbage Collection Algorithm

The total number of verification conditions is 328

lemma *Mul-Gar-Coll*:
 ||– {*Mul-Proper* *n* ∧ *Mul-mut-init* *n* ∧ (∀ *i* < *n*. *Z* (*Muts!**i*))}
 COBEGIN
 Mul-Collector *n*
 {*False*}
 ||
 SCHEME [0 ≤ *j* < *n*]
 Mul-Mutator *j n*
 {*False*}
 COEND
 {*False*}
 ⟨*proof*⟩

end

Chapter 3

The Rely-Guarantee Method

3.1 Abstract Syntax

```
theory RG-Com imports Main begin
```

Semantics of assertions and boolean expressions (*bexp*) as sets of states.
Syntax of commands *com* and parallel commands *par-com*.

```
type-synonym 'a bexp = 'a set
```

```
datatype 'a com =  
  Basic 'a  $\Rightarrow$  'a  
  | Seq 'a com 'a com  
  | Cond 'a bexp 'a com 'a com  
  | While 'a bexp 'a com  
  | Await 'a bexp 'a com
```

```
type-synonym 'a par-com = 'a com option list
```

```
end
```

3.2 Operational Semantics

```
theory RG-Tran  
imports RG-Com  
begin
```

3.2.1 Semantics of Component Programs

Environment transitions

```
type-synonym 'a conf = (('a com) option)  $\times$  'a
```

inductive-set

```
etran :: ('a conf  $\times$  'a conf) set  
and etran' :: 'a conf  $\Rightarrow$  'a conf  $\Rightarrow$  bool ( $\langle \cdot \rangle$   $\rightarrow$   $\rightarrow$  [81,81] 80)
```

where

$P -e\rightarrow Q \equiv (P, Q) \in etran$
| $Env: (P, s) -e\rightarrow (P, t)$

lemma $etranE: c -e\rightarrow c' \implies (\bigwedge P s t. c = (P, s) \implies c' = (P, t) \implies Q) \implies Q$
{proof}

Component transitions

inductive-set

$ctran :: ('a\ conf \times 'a\ conf)\ set$
and $ctran' :: 'a\ conf \Rightarrow 'a\ conf \Rightarrow bool$ ($\langle - -c\rightarrow - \rangle [81,81] 80$)
and $ctrans :: 'a\ conf \Rightarrow 'a\ conf \Rightarrow bool$ ($\langle - -c*\rightarrow - \rangle [81,81] 80$)

where

$P -c\rightarrow Q \equiv (P, Q) \in ctran$
| $P -c*\rightarrow Q \equiv (P, Q) \in ctran^*$

| $Basic: (Some(Basic\ f), s) -c\rightarrow (None, f\ s)$

| $Seq1: (Some\ P0, s) -c\rightarrow (None, t) \implies (Some(Seq\ P0\ P1), s) -c\rightarrow (Some\ P1, t)$

| $Seq2: (Some\ P0, s) -c\rightarrow (Some\ P2, t) \implies (Some(Seq\ P0\ P1), s) -c\rightarrow (Some(Seq\ P2\ P1), t)$

| $CondT: s \in b \implies (Some(Cond\ b\ P1\ P2), s) -c\rightarrow (Some\ P1, s)$

| $CondF: s \notin b \implies (Some(Cond\ b\ P1\ P2), s) -c\rightarrow (Some\ P2, s)$

| $WhileF: s \notin b \implies (Some(While\ b\ P), s) -c\rightarrow (None, s)$

| $WhileT: s \in b \implies (Some(While\ b\ P), s) -c\rightarrow (Some(Seq\ P\ (While\ b\ P)), s)$

| $Await: \llbracket s \in b; (Some\ P, s) -c*\rightarrow (None, t) \rrbracket \implies (Some(Await\ b\ P), s) -c\rightarrow (None, t)$

monos $rtrancl\text{-}mono$

3.2.2 Semantics of Parallel Programs

type-synonym $'a\ par\text{-}conf = ('a\ par\text{-}com) \times 'a$

inductive-set

$par\text{-}etran :: ('a\ par\text{-}conf \times 'a\ par\text{-}conf)\ set$
and $par\text{-}etran' :: ['a\ par\text{-}conf, 'a\ par\text{-}conf] \Rightarrow bool$ ($\langle - -pe\rightarrow - \rangle [81,81] 80$)

where

$P -pe\rightarrow Q \equiv (P, Q) \in par\text{-}etran$
| $ParEnv: (Ps, s) -pe\rightarrow (Ps, t)$

inductive-set

$par\text{-}ctran :: ('a\ par\text{-}conf \times 'a\ par\text{-}conf)\ set$
and $par\text{-}ctran' :: ['a\ par\text{-}conf, 'a\ par\text{-}conf] \Rightarrow bool$ ($\langle - -pc\rightarrow - \rangle [81,81] 80$)

where

$P -pc \rightarrow Q \equiv (P, Q) \in \text{par-ctran}$
 $| \text{ParComp}: \llbracket i < \text{length } Ps; (Ps!i, s) -c \rightarrow (r, t) \rrbracket \Longrightarrow (Ps, s) -pc \rightarrow (Ps[i:=r], t)$

lemma $\text{par-ctranE}: c -pc \rightarrow c' \Longrightarrow$

$(\bigwedge i \text{ Ps } s \ r \ t. c = (Ps, s) \Longrightarrow c' = (Ps[i := r], t) \Longrightarrow i < \text{length } Ps \Longrightarrow$
 $(Ps ! i, s) -c \rightarrow (r, t) \Longrightarrow P) \Longrightarrow P$

$\langle \text{proof} \rangle$

3.2.3 Computations

Sequential computations

type-synonym $'a \text{ confs} = 'a \text{ conf list}$

inductive-set $\text{cptn} :: 'a \text{ confs set}$

where

$\text{CptnOne}: \llbracket (P, s) \rrbracket \in \text{cptn}$
 $| \text{CptnEnv}: (P, t) \# xs \in \text{cptn} \Longrightarrow (P, s) \# (P, t) \# xs \in \text{cptn}$
 $| \text{CptnComp}: \llbracket (P, s) -c \rightarrow (Q, t); (Q, t) \# xs \in \text{cptn} \rrbracket \Longrightarrow (P, s) \# (Q, t) \# xs \in \text{cptn}$

definition $\text{cp} :: ('a \text{ com}) \text{ option} \Rightarrow 'a \Rightarrow ('a \text{ confs}) \text{ set}$ **where**

$\text{cp } P \ s \equiv \{l. !!0=(P, s) \wedge l \in \text{cptn}\}$

Parallel computations

type-synonym $'a \text{ par-confcs} = 'a \text{ par-conf list}$

inductive-set $\text{par-cptn} :: 'a \text{ par-confcs set}$

where

$\text{ParCptnOne}: \llbracket (P, s) \rrbracket \in \text{par-cptn}$
 $| \text{ParCptnEnv}: (P, t) \# xs \in \text{par-cptn} \Longrightarrow (P, s) \# (P, t) \# xs \in \text{par-cptn}$
 $| \text{ParCptnComp}: \llbracket (P, s) -pc \rightarrow (Q, t); (Q, t) \# xs \in \text{par-cptn} \rrbracket \Longrightarrow (P, s) \# (Q, t) \# xs \in \text{par-cptn}$

definition $\text{par-cp} :: 'a \text{ par-com} \Rightarrow 'a \Rightarrow ('a \text{ par-confcs}) \text{ set}$ **where**

$\text{par-cp } P \ s \equiv \{l. !!0=(P, s) \wedge l \in \text{par-cptn}\}$

3.2.4 Modular Definition of Computation

definition $\text{lift} :: 'a \text{ com} \Rightarrow 'a \text{ conf} \Rightarrow 'a \text{ conf}$ **where**

$\text{lift } Q \equiv \lambda(P, s). (\text{if } P = \text{None then } (\text{Some } Q, s) \text{ else } (\text{Some } (\text{Seq } (\text{the } P) \ Q), s))$

inductive-set $\text{cptn-mod} :: ('a \text{ confs}) \text{ set}$

where

$\text{CptnModOne}: \llbracket (P, s) \rrbracket \in \text{cptn-mod}$
 $| \text{CptnModEnv}: (P, t) \# xs \in \text{cptn-mod} \Longrightarrow (P, s) \# (P, t) \# xs \in \text{cptn-mod}$
 $| \text{CptnModNone}: \llbracket (\text{Some } P, s) -c \rightarrow (\text{None}, t); (\text{None}, t) \# xs \in \text{cptn-mod} \rrbracket \Longrightarrow$
 $(\text{Some } P, s) \# (\text{None}, t) \# xs \in \text{cptn-mod}$

$| \text{CptnModCondT}: \llbracket (\text{Some } P0, s) \# ys \in \text{cptn-mod}; s \in b \rrbracket \implies (\text{Some}(\text{Cond } b P0 P1), s) \# (\text{Some } P0, s) \# ys \in \text{cptn-mod}$
 $| \text{CptnModCondF}: \llbracket (\text{Some } P1, s) \# ys \in \text{cptn-mod}; s \notin b \rrbracket \implies (\text{Some}(\text{Cond } b P0 P1), s) \# (\text{Some } P1, s) \# ys \in \text{cptn-mod}$
 $| \text{CptnModSeq1}: \llbracket (\text{Some } P0, s) \# xs \in \text{cptn-mod}; zs = \text{map } (\text{lift } P1) \text{ } xs \rrbracket \implies (\text{Some}(\text{Seq } P0 P1), s) \# zs \in \text{cptn-mod}$
 $| \text{CptnModSeq2}: \llbracket (\text{Some } P0, s) \# xs \in \text{cptn-mod}; \text{fst}(\text{last } ((\text{Some } P0, s) \# xs)) = \text{None}; (\text{Some } P1, \text{snd}(\text{last } ((\text{Some } P0, s) \# xs))) \# ys \in \text{cptn-mod}; zs = (\text{map } (\text{lift } P1) \text{ } xs) @ ys \rrbracket \implies (\text{Some}(\text{Seq } P0 P1), s) \# zs \in \text{cptn-mod}$
 $| \text{CptnModWhile1}: \llbracket (\text{Some } P, s) \# xs \in \text{cptn-mod}; s \in b; zs = \text{map } (\text{lift } (\text{While } b P)) \text{ } xs \rrbracket \implies (\text{Some}(\text{While } b P), s) \# (\text{Some}(\text{Seq } P (\text{While } b P)), s) \# zs \in \text{cptn-mod}$
 $| \text{CptnModWhile2}: \llbracket (\text{Some } P, s) \# xs \in \text{cptn-mod}; \text{fst}(\text{last } ((\text{Some } P, s) \# xs)) = \text{None}; s \in b; zs = (\text{map } (\text{lift } (\text{While } b P)) \text{ } xs) @ ys; (\text{Some}(\text{While } b P), \text{snd}(\text{last } ((\text{Some } P, s) \# xs))) \# ys \in \text{cptn-mod} \rrbracket \implies (\text{Some}(\text{While } b P), s) \# (\text{Some}(\text{Seq } P (\text{While } b P)), s) \# zs \in \text{cptn-mod}$

3.2.5 Equivalence of Both Definitions.

lemma *last-length*: $((a \# xs) \# (\text{length } xs)) = \text{last } (a \# xs)$
 $\langle \text{proof} \rangle$

lemma *div-seq [rule-format]*: $\text{list} \in \text{cptn-mod} \implies$
 $(\forall s P Q zs. \text{list} = (\text{Some } (\text{Seq } P Q), s) \# zs \longrightarrow$
 $(\exists xs. (\text{Some } P, s) \# xs \in \text{cptn-mod} \wedge (zs = (\text{map } (\text{lift } Q) \text{ } xs) \vee$
 $(\text{fst}(((\text{Some } P, s) \# xs) \# \text{length } xs)) = \text{None} \wedge$
 $(\exists ys. (\text{Some } Q, \text{snd}(((\text{Some } P, s) \# xs) \# \text{length } xs))) \# ys \in \text{cptn-mod}$
 $\wedge zs = (\text{map } (\text{lift } (Q)) \text{ } xs) @ ys))))$
 $\langle \text{proof} \rangle$

lemma *cptn-onlyif-cptn-mod-aux [rule-format]*:
 $\forall s Q t xs. ((\text{Some } a, s), Q, t) \in \text{ctran} \longrightarrow (Q, t) \# xs \in \text{cptn-mod}$
 $\longrightarrow (\text{Some } a, s) \# (Q, t) \# xs \in \text{cptn-mod}$
 $\langle \text{proof} \rangle$

lemma *cptn-onlyif-cptn-mod [rule-format]*: $c \in \text{cptn} \implies c \in \text{cptn-mod}$
 $\langle \text{proof} \rangle$

lemma *lift-is-cptn*: $c \in \text{cptn} \implies \text{map } (\text{lift } P) \text{ } c \in \text{cptn}$
 $\langle \text{proof} \rangle$

lemma *cptn-append-is-cptn [rule-format]*:
 $\forall b a. b \# c1 \in \text{cptn} \longrightarrow a \# c2 \in \text{cptn} \longrightarrow (b \# c1) \# \text{length } c1 = a \longrightarrow b \# c1 @ c2 \in \text{cptn}$
 $\langle \text{proof} \rangle$

lemma *last-lift*: $\llbracket xs \neq []; \text{fst}(xs \# (\text{length } xs - (\text{Suc } 0))) = \text{None} \rrbracket$

$\implies \text{fst}((\text{map } (\text{lift } P) \text{ xs})!(\text{length } (\text{map } (\text{lift } P) \text{ xs}) - (\text{Suc } 0))) = (\text{Some } P)$
 ⟨proof⟩

lemma *last-fst* [rule-format]: $P((a\#x)!\text{length } x) \longrightarrow \neg P \ a \longrightarrow P \ (x!(\text{length } x - (\text{Suc } 0)))$
 ⟨proof⟩

lemma *last-fst-esp*:
 $\text{fst}(((\text{Some } a,s)\#xs)!(\text{length } xs)) = \text{None} \implies \text{fst}(xs!(\text{length } xs - (\text{Suc } 0))) = \text{None}$
 ⟨proof⟩

lemma *last-snd*: $xs \neq [] \implies$
 $\text{snd}(((\text{map } (\text{lift } P) \text{ xs})!(\text{length } (\text{map } (\text{lift } P) \text{ xs}) - (\text{Suc } 0))) = \text{snd}(xs!(\text{length } xs - (\text{Suc } 0)))$
 ⟨proof⟩

lemma *Cons-lift*: $(\text{Some } (\text{Seq } P \ Q), s) \# (\text{map } (\text{lift } Q) \text{ xs}) = \text{map } (\text{lift } Q) ((\text{Some } P, s) \# xs)$
 ⟨proof⟩

lemma *Cons-lift-append*:
 $(\text{Some } (\text{Seq } P \ Q), s) \# (\text{map } (\text{lift } Q) \text{ xs}) @ ys = \text{map } (\text{lift } Q) ((\text{Some } P, s) \# xs) @ ys$
 ⟨proof⟩

lemma *lift-nth*: $i < \text{length } xs \implies \text{map } (\text{lift } Q) \text{ xs } ! i = \text{lift } Q \ (xs ! i)$
 ⟨proof⟩

lemma *snd-lift*: $i < \text{length } xs \implies \text{snd}(\text{lift } Q \ (xs ! i)) = \text{snd} \ (xs ! i)$
 ⟨proof⟩

lemma *cptn-iff-cptn-mod*: $c \in \text{cptn-mod} \implies c \in \text{cptn}$
 ⟨proof⟩

theorem *cptn-iff-cptn-mod*: $(c \in \text{cptn}) = (c \in \text{cptn-mod})$
 ⟨proof⟩

3.3 Validity of Correctness Formulas

3.3.1 Validity for Component Programs.

type-synonym $'a \text{ rgformula} =$
 $'a \text{ com} \times 'a \text{ set} \times ('a \times 'a) \text{ set} \times ('a \times 'a) \text{ set} \times 'a \text{ set}$

definition *assum* :: $('a \text{ set} \times ('a \times 'a) \text{ set}) \Rightarrow ('a \text{ confs}) \text{ set}$ **where**
 $\text{assum} \equiv \lambda(\text{pre}, \text{rely}). \{c. \text{snd}(c!0) \in \text{pre} \wedge (\forall i. \text{Suc } i < \text{length } c \longrightarrow$
 $c!i - e \rightarrow c!(\text{Suc } i) \longrightarrow (\text{snd}(c!i), \text{snd}(c!\text{Suc } i)) \in \text{rely})\}$

definition *comm* :: $(('a \times 'a) \text{ set} \times 'a \text{ set}) \Rightarrow ('a \text{ confs}) \text{ set}$ **where**

$comm \equiv \lambda(guar, post). \{c. (\forall i. Suc\ i < length\ c \longrightarrow$
 $c!i - c \rightarrow c!(Suc\ i) \longrightarrow (snd(c!i), snd(c!Suc\ i)) \in guar) \wedge$
 $(fst(last\ c) = None \longrightarrow snd(last\ c) \in post)\}$

definition *com-validity* :: 'a com \Rightarrow 'a set \Rightarrow ('a \times 'a) set \Rightarrow ('a \times 'a) set \Rightarrow 'a set \Rightarrow bool

(\models - sat [-, -, -, -] [60,0,0,0,0] 45) **where**
 $\models P\ sat\ [pre, rely, guar, post] \equiv$
 $\forall s. cp\ (Some\ P)\ s \cap assum(pre, rely) \subseteq comm(guar, post)$

3.3.2 Validity for Parallel Programs.

definition *All-None* :: ('a com) list \Rightarrow bool **where**

All-None xs $\equiv \forall c \in set\ xs. c = None$

definition *par-assum* :: ('a set \times ('a \times 'a) set) \Rightarrow ('a par-confs) set **where**

par-assum $\equiv \lambda(pre, rely). \{c. snd(c!0) \in pre \wedge (\forall i. Suc\ i < length\ c \longrightarrow$
 $c!i - pc \rightarrow c!Suc\ i \longrightarrow (snd(c!i), snd(c!Suc\ i)) \in rely)\}$

definition *par-comm* :: (('a \times 'a) set \times 'a set) \Rightarrow ('a par-confs) set **where**

par-comm $\equiv \lambda(guar, post). \{c. (\forall i. Suc\ i < length\ c \longrightarrow$
 $c!i - pc \rightarrow c!Suc\ i \longrightarrow (snd(c!i), snd(c!Suc\ i)) \in guar) \wedge$
 $(All-None\ (fst\ (last\ c)) \longrightarrow snd\ (last\ c) \in post)\}$

definition *par-com-validity* :: 'a par-com \Rightarrow 'a set \Rightarrow ('a \times 'a) set \Rightarrow ('a \times 'a) set

\Rightarrow 'a set \Rightarrow bool (\models - SAT [-, -, -, -] [60,0,0,0,0] 45) **where**
 $\models Ps\ SAT\ [pre, rely, guar, post] \equiv$
 $\forall s. par-cp\ Ps\ s \cap par-assum(pre, rely) \subseteq par-comm(guar, post)$

3.3.3 Compositionality of the Semantics

Definition of the conjoin operator

definition *same-length* :: 'a par-confs \Rightarrow ('a confs) list \Rightarrow bool **where**

same-length c clist $\equiv (\forall i < length\ clist. length(clist!i) = length\ c)$

definition *same-state* :: 'a par-confs \Rightarrow ('a confs) list \Rightarrow bool **where**

same-state c clist $\equiv (\forall i < length\ clist. \forall j < length\ c. snd(c!j) = snd((clist!i)!j))$

definition *same-program* :: 'a par-confs \Rightarrow ('a confs) list \Rightarrow bool **where**

same-program c clist $\equiv (\forall j < length\ c. fst(c!j) = map\ (\lambda x. fst(nth\ x\ j))\ clist)$

definition *compat-label* :: 'a par-confs \Rightarrow ('a confs) list \Rightarrow bool **where**

compat-label c clist $\equiv (\forall j. Suc\ j < length\ c \longrightarrow$
 $(c!j - pc \rightarrow c!Suc\ j \wedge (\exists i < length\ clist. (clist!i)!j - c \rightarrow (clist!i)! Suc\ j \wedge$
 $(\forall l < length\ clist. l \neq i \longrightarrow (clist!l)!j - e \rightarrow (clist!l)! Suc\ j))) \vee$
 $(c!j - pe \rightarrow c!Suc\ j \wedge (\forall i < length\ clist. (clist!i)!j - e \rightarrow (clist!i)! Suc\ j))$

definition *conjoin* :: 'a par-confs \Rightarrow ('a confs) list \Rightarrow bool (\leftarrow \propto \rightarrow [65,65] 64)
where
 $c \propto clist \equiv (same-length\ c\ clist) \wedge (same-state\ c\ clist) \wedge (same-program\ c\ clist)$
 $\wedge (compat-label\ c\ clist)$

Some previous lemmas

lemma *list-eq-if* [rule-format]:

$\forall ys. xs=ys \longrightarrow (length\ xs = length\ ys) \longrightarrow (\forall i < length\ xs. xs!i=ys!i)$
 $\langle proof \rangle$

lemma *list-eq*: $(length\ xs = length\ ys \wedge (\forall i < length\ xs. xs!i=ys!i)) = (xs=ys)$
 $\langle proof \rangle$

lemma *nth-tl*: $\llbracket ys!0=a; ys \neq [] \rrbracket \Longrightarrow ys=(a\#\ (tl\ ys))$
 $\langle proof \rangle$

lemma *nth-tl-if* [rule-format]: $ys \neq [] \longrightarrow ys!0=a \longrightarrow P\ ys \longrightarrow P\ (a\#\ (tl\ ys))$
 $\langle proof \rangle$

lemma *nth-tl-onlyif* [rule-format]: $ys \neq [] \longrightarrow ys!0=a \longrightarrow P\ (a\#\ (tl\ ys)) \longrightarrow P\ ys$
 $\langle proof \rangle$

lemma *seq-not-eq1*: $Seq\ c1\ c2 \neq c1$
 $\langle proof \rangle$

lemma *seq-not-eq2*: $Seq\ c1\ c2 \neq c2$
 $\langle proof \rangle$

lemma *if-not-eq1*: $Cond\ b\ c1\ c2 \neq c1$
 $\langle proof \rangle$

lemma *if-not-eq2*: $Cond\ b\ c1\ c2 \neq c2$
 $\langle proof \rangle$

lemmas *seq-and-if-not-eq* [simp] = *seq-not-eq1 seq-not-eq2*
seq-not-eq1 [THEN not-sym] *seq-not-eq2* [THEN not-sym]
if-not-eq1 if-not-eq2 if-not-eq1 [THEN not-sym] *if-not-eq2* [THEN not-sym]

lemma *prog-not-eq-in-ctran-aux*:
assumes $c: (P,s) -c \rightarrow (Q,t)$
shows $P \neq Q$ $\langle proof \rangle$

lemma *prog-not-eq-in-ctran* [simp]: $\neg (P,s) -c \rightarrow (P,t)$
 $\langle proof \rangle$

lemma *prog-not-eq-in-par-ctran-aux* [rule-format]: $(P,s) -pc \rightarrow (Q,t) \Longrightarrow (P \neq Q)$
 $\langle proof \rangle$

lemma *prog-not-eq-in-par-ctran* [*simp*]: $\neg (P, s) -pc \rightarrow (P, t)$
 ⟨*proof*⟩

lemma *tl-in-cptn*: $\llbracket a \# xs \in cptn; xs \neq [] \rrbracket \implies xs \in cptn$
 ⟨*proof*⟩

lemma *tl-zero*[*rule-format*]:
 $P (ys!Suc j) \rightarrow Suc j < length\ ys \rightarrow ys \neq [] \rightarrow P (tl(ys)!j)$
 ⟨*proof*⟩

3.3.4 The Semantics is Compositional

lemma *aux-if* [*rule-format*]:
 $\forall xs\ s\ clist. (length\ clist = length\ xs \wedge (\forall i < length\ xs. (xs!i, s) \# clist!i \in cptn) \wedge ((xs, s) \# ys \propto map\ (\lambda i. (fst\ i, s) \# snd\ i)\ (zip\ xs\ clist))) \rightarrow (xs, s) \# ys \in par-cptn$
 ⟨*proof*⟩

lemma *aux-onlyif* [*rule-format*]: $\forall xs\ s. (xs, s) \# ys \in par-cptn \rightarrow (\exists clist. (length\ clist = length\ xs) \wedge (xs, s) \# ys \propto map\ (\lambda i. (fst\ i, s) \# (snd\ i))\ (zip\ xs\ clist) \wedge (\forall i < length\ xs. (xs!i, s) \# (clist!i) \in cptn))$
 ⟨*proof*⟩

lemma *one-iff-aux*: $xs \neq [] \implies (\forall ys. ((xs, s) \# ys \in par-cptn) = (\exists clist. length\ clist = length\ xs \wedge ((xs, s) \# ys \propto map\ (\lambda i. (fst\ i, s) \# (snd\ i))\ (zip\ xs\ clist)) \wedge (\forall i < length\ xs. (xs!i, s) \# (clist!i) \in cptn))) = (par-cp\ (xs)\ s = \{c. \exists clist. (length\ clist) = (length\ xs) \wedge (\forall i < length\ clist. (clist!i) \in cp(xs!i)\ s) \wedge c \propto clist\})$
 ⟨*proof*⟩

theorem *one*: $xs \neq [] \implies par-cp\ xs\ s = \{c. \exists clist. (length\ clist) = (length\ xs) \wedge (\forall i < length\ clist. (clist!i) \in cp(xs!i)\ s) \wedge c \propto clist\}$
 ⟨*proof*⟩

end

3.4 The Proof System

theory *RG-Hoare* imports *RG-Tran* begin

3.4.1 Proof System for Component Programs

declare *Un-subset-iff* [*simp del*] *sup.bounded-iff* [*simp del*]

definition *stable* :: $'a\ set \Rightarrow ('a \times 'a)\ set \Rightarrow bool$ **where**
 $stable \equiv \lambda f\ g. (\forall x\ y. x \in f \rightarrow (x, y) \in g \rightarrow y \in f)$

inductive

$rghoare :: ['a\ com, 'a\ set, ('a \times 'a)\ set, ('a \times 'a)\ set, 'a\ set] \Rightarrow bool$
 $(\langle \vdash -\ sat [-, -, -, -] [60,0,0,0,0] 45 \rangle)$

where

$Basic: \llbracket pre \subseteq \{s.\ f\ s \in post\}; \{(s,t).\ s \in pre \wedge (t=f\ s \vee t=s)\} \subseteq guar;$
 $\quad stable\ pre\ rely; stable\ post\ rely \rrbracket$
 $\implies \vdash Basic\ f\ sat [pre, rely, guar, post]$

| $Seq: \llbracket \vdash P\ sat [pre, rely, guar, mid]; \vdash Q\ sat [mid, rely, guar, post] \rrbracket$
 $\implies \vdash Seq\ P\ Q\ sat [pre, rely, guar, post]$

| $Cond: \llbracket stable\ pre\ rely; \vdash P1\ sat [pre \cap b, rely, guar, post];$
 $\quad \vdash P2\ sat [pre \cap \neg b, rely, guar, post]; \forall s.\ (s,s) \in guar \rrbracket$
 $\implies \vdash Cond\ b\ P1\ P2\ sat [pre, rely, guar, post]$

| $While: \llbracket stable\ pre\ rely; (pre \cap \neg b) \subseteq post; stable\ post\ rely;$
 $\quad \vdash P\ sat [pre \cap b, rely, guar, pre]; \forall s.\ (s,s) \in guar \rrbracket$
 $\implies \vdash While\ b\ P\ sat [pre, rely, guar, post]$

| $Await: \llbracket stable\ pre\ rely; stable\ post\ rely;$
 $\quad \forall V.\ \vdash P\ sat [pre \cap b \cap \{V\}, \{(s,t).\ s = t\},$
 $\quad UNIV, \{s.\ (V, s) \in guar\} \cap post] \rrbracket$
 $\implies \vdash Await\ b\ P\ sat [pre, rely, guar, post]$

| $Conseq: \llbracket pre \subseteq pre'; rely \subseteq rely'; guar' \subseteq guar; post' \subseteq post;$
 $\quad \vdash P\ sat [pre', rely', guar', post'] \rrbracket$
 $\implies \vdash P\ sat [pre, rely, guar, post]$

definition $Pre :: 'a\ rgformula \Rightarrow 'a\ set$ **where**

$Pre\ x \equiv fst(snd\ x)$

definition $Post :: 'a\ rgformula \Rightarrow 'a\ set$ **where**

$Post\ x \equiv snd(snd(snd(snd\ x)))$

definition $Rely :: 'a\ rgformula \Rightarrow ('a \times 'a)\ set$ **where**

$Rely\ x \equiv fst(snd(snd\ x))$

definition $Guar :: 'a\ rgformula \Rightarrow ('a \times 'a)\ set$ **where**

$Guar\ x \equiv snd(snd(snd(snd\ x)))$

definition $Com :: 'a\ rgformula \Rightarrow 'a\ com$ **where**

$Com\ x \equiv fst\ x$

3.4.2 Proof System for Parallel Programs

type-synonym $'a\ par\ rgformula =$

$('a\ rgformula)\ list \times 'a\ set \times ('a \times 'a)\ set \times ('a \times 'a)\ set \times 'a\ set$

inductive

$par\text{-}rg\text{hoare} :: ('a\ rg\text{formula})\ list \Rightarrow 'a\ set \Rightarrow ('a \times 'a)\ set \Rightarrow ('a \times 'a)\ set \Rightarrow 'a\ set \Rightarrow bool$

$\langle \vdash - SAT [-, -, -, -] [60,0,0,0,0] 45 \rangle$

where

Parallel:

$\llbracket \forall i < length\ xs.\ rely \cup (\bigcup j \in \{j.\ j < length\ xs \wedge j \neq i\}.\ Guar(xs!j)) \subseteq Rely(xs!i);$

$(\bigcup j \in \{j.\ j < length\ xs\}.\ Guar(xs!j)) \subseteq guar;$

$pre \subseteq (\bigcap i \in \{i.\ i < length\ xs\}.\ Pre(xs!i));$

$(\bigcap i \in \{i.\ i < length\ xs\}.\ Post(xs!i)) \subseteq post;$

$\forall i < length\ xs.\ \vdash Com(xs!i)\ sat [Pre(xs!i), Rely(xs!i), Guar(xs!i), Post(xs!i)] \rrbracket$

$\implies \vdash xs\ SAT [pre, rely, guar, post]$

3.5 Soundness

Some previous lemmas

lemma *tl-of-assum-in-assum:*

$(P, s) \# (P, t) \# xs \in assum\ (pre, rely) \implies stable\ pre\ rely$

$\implies (P, t) \# xs \in assum\ (pre, rely)$

$\langle proof \rangle$

lemma *etran-in-comm:*

$(P, t) \# xs \in comm(guar, post) \implies (P, s) \# (P, t) \# xs \in comm(guar, post)$

$\langle proof \rangle$

lemma *ctran-in-comm:*

$\llbracket (s, s) \in guar; (Q, s) \# xs \in comm(guar, post) \rrbracket$

$\implies (P, s) \# (Q, s) \# xs \in comm(guar, post)$

$\langle proof \rangle$

lemma *takecptn-is-cptn [rule-format, elim!]:*

$\forall j.\ c \in cptn \longrightarrow take\ (Suc\ j)\ c \in cptn$

$\langle proof \rangle$

lemma *dropcptn-is-cptn [rule-format, elim!]:*

$\forall j < length\ c.\ c \in cptn \longrightarrow drop\ j\ c \in cptn$

$\langle proof \rangle$

lemma *takepar-cptn-is-par-cptn [rule-format, elim]:*

$\forall j.\ c \in par\text{-}cptn \longrightarrow take\ (Suc\ j)\ c \in par\text{-}cptn$

$\langle proof \rangle$

lemma *droppar-cptn-is-par-cptn [rule-format]:*

$\forall j < length\ c.\ c \in par\text{-}cptn \longrightarrow drop\ j\ c \in par\text{-}cptn$

$\langle proof \rangle$

lemma *tl-of-cptn-is-cptn:* $\llbracket x \# xs \in cptn; xs \neq [] \rrbracket \implies xs \in cptn$

$\langle proof \rangle$

lemma *not-ctran-None* [rule-format]:

$\forall s. (None, s) \# xs \in \text{cptn} \longrightarrow (\forall i < \text{length } xs. ((None, s) \# xs)!i -e \longrightarrow xs!i)$
 ⟨proof⟩

lemma *cptn-not-empty* [simp]: $[] \notin \text{cptn}$

⟨proof⟩

lemma *etran-or-ctran* [rule-format]:

$\forall m i. x \in \text{cptn} \longrightarrow m \leq \text{length } x$
 $\longrightarrow (\forall i. \text{Suc } i < m \longrightarrow \neg x!i -c \longrightarrow x!\text{Suc } i) \longrightarrow \text{Suc } i < m$
 $\longrightarrow x!i -e \longrightarrow x!\text{Suc } i$
 ⟨proof⟩

lemma *etran-or-ctran2* [rule-format]:

$\forall i. \text{Suc } i < \text{length } x \longrightarrow x \in \text{cptn} \longrightarrow (x!i -c \longrightarrow x!\text{Suc } i \longrightarrow \neg x!i -e \longrightarrow x!\text{Suc } i)$
 $\vee (x!i -e \longrightarrow x!\text{Suc } i \longrightarrow \neg x!i -c \longrightarrow x!\text{Suc } i)$
 ⟨proof⟩

lemma *etran-or-ctran2-disjI1*:

$\llbracket x \in \text{cptn}; \text{Suc } i < \text{length } x; x!i -c \longrightarrow x!\text{Suc } i \rrbracket \Longrightarrow \neg x!i -e \longrightarrow x!\text{Suc } i$
 ⟨proof⟩

lemma *etran-or-ctran2-disjI2*:

$\llbracket x \in \text{cptn}; \text{Suc } i < \text{length } x; x!i -e \longrightarrow x!\text{Suc } i \rrbracket \Longrightarrow \neg x!i -c \longrightarrow x!\text{Suc } i$
 ⟨proof⟩

lemma *not-ctran-None2* [rule-format]:

$\llbracket (None, s) \# xs \in \text{cptn}; i < \text{length } xs \rrbracket \Longrightarrow \neg ((None, s) \# xs)!i -c \longrightarrow xs!i$
 ⟨proof⟩

lemma *Ex-first-occurrence* [rule-format]: $P (n::\text{nat}) \longrightarrow (\exists m. P m \wedge (\forall i < m. \neg P i))$

⟨proof⟩

lemma *stability* [rule-format]:

$\forall j k. x \in \text{cptn} \longrightarrow \text{stable } p \text{ rely} \longrightarrow j \leq k \longrightarrow k < \text{length } x \longrightarrow \text{snd}(x!j) \in p \longrightarrow$
 $(\forall i. (\text{Suc } i) < \text{length } x \longrightarrow$
 $(x!i -e \longrightarrow x!(\text{Suc } i)) \longrightarrow (\text{snd}(x!i), \text{snd}(x!(\text{Suc } i))) \in \text{rely}) \longrightarrow$
 $(\forall i. j \leq i \wedge i < k \longrightarrow x!i -e \longrightarrow x!\text{Suc } i) \longrightarrow \text{snd}(x!k) \in p \wedge \text{fst}(x!j) = \text{fst}(x!k)$
 ⟨proof⟩

3.5.1 Soundness of the System for Component Programs

Soundness of the Basic rule

lemma *unique-ctran-Basic* [rule-format]:

$\forall s i. x \in \text{cptn} \longrightarrow x!0 = (\text{Some } (\text{Basic } f), s) \longrightarrow$
 $\text{Suc } i < \text{length } x \longrightarrow x!i -c \longrightarrow x!\text{Suc } i \longrightarrow$
 $(\forall j. \text{Suc } j < \text{length } x \longrightarrow i \neq j \longrightarrow x!j -e \longrightarrow x!\text{Suc } j)$

$\langle \text{proof} \rangle$

lemma *exists-ctran-Basic-None* [rule-format]:

$\forall s i. x \in \text{cptn} \longrightarrow x ! 0 = (\text{Some } (\text{Basic } f), s)$
 $\longrightarrow i < \text{length } x \longrightarrow \text{fst}(x!i) = \text{None} \longrightarrow (\exists j < i. x!j -c \rightarrow x! \text{Suc } j)$

$\langle \text{proof} \rangle$

lemma *Basic-sound*:

$\llbracket \text{pre} \subseteq \{s. f s \in \text{post}\}; \{(s, t). s \in \text{pre} \wedge t = f s\} \subseteq \text{guar};$
stable pre rely; stable post rely
 $\implies \models \text{Basic } f \text{ sat } [\text{pre}, \text{rely}, \text{guar}, \text{post}]$
 $\langle \text{proof} \rangle$

Soundness of the Await rule

lemma *unique-ctran-Await* [rule-format]:

$\forall s i. x \in \text{cptn} \longrightarrow x ! 0 = (\text{Some } (\text{Await } b c), s) \longrightarrow$
 $\text{Suc } i < \text{length } x \longrightarrow x!i -c \rightarrow x! \text{Suc } i \longrightarrow$
 $(\forall j. \text{Suc } j < \text{length } x \longrightarrow i \neq j \longrightarrow x!j -e \rightarrow x! \text{Suc } j)$

$\langle \text{proof} \rangle$

lemma *exists-ctran-Await-None* [rule-format]:

$\forall s i. x \in \text{cptn} \longrightarrow x ! 0 = (\text{Some } (\text{Await } b c), s)$
 $\longrightarrow i < \text{length } x \longrightarrow \text{fst}(x!i) = \text{None} \longrightarrow (\exists j < i. x!j -c \rightarrow x! \text{Suc } j)$

$\langle \text{proof} \rangle$

lemma *Star-imp-cptn*:

$(P, s) -c^* \rightarrow (R, t) \implies \exists l \in \text{cp } P s. (\text{last } l) = (R, t)$
 $\wedge (\forall i. \text{Suc } i < \text{length } l \longrightarrow !i -c \rightarrow ! \text{Suc } i)$

$\langle \text{proof} \rangle$

lemma *Await-sound*:

$\llbracket \text{stable pre rely; stable post rely};$
 $\forall V. \vdash P \text{ sat } [\text{pre} \cap b \cap \{s. s = V\}, \{(s, t). s = t\},$
 $\text{UNIV}, \{s. (V, s) \in \text{guar}\} \cap \text{post}] \wedge$
 $\models P \text{ sat } [\text{pre} \cap b \cap \{s. s = V\}, \{(s, t). s = t\},$
 $\text{UNIV}, \{s. (V, s) \in \text{guar}\} \cap \text{post}] \rrbracket$
 $\implies \models \text{Await } b P \text{ sat } [\text{pre}, \text{rely}, \text{guar}, \text{post}]$

$\langle \text{proof} \rangle$

Soundness of the Conditional rule

lemma *Cond-sound*:

$\llbracket \text{stable pre rely}; \models P1 \text{ sat } [\text{pre} \cap b, \text{rely}, \text{guar}, \text{post}];$
 $\models P2 \text{ sat } [\text{pre} \cap \neg b, \text{rely}, \text{guar}, \text{post}]; \forall s. (s, s) \in \text{guar} \rrbracket$
 $\implies \models (\text{Cond } b P1 P2) \text{ sat } [\text{pre}, \text{rely}, \text{guar}, \text{post}]$

$\langle \text{proof} \rangle$

Soundness of the Sequential rule

inductive-cases *Seq-cases* [*elim!*]: $(\text{Some } (\text{Seq } P \ Q), s) \text{ --c--} t$

lemma *last-lift-not-None*: $\text{fst } ((\text{lift } Q) ((x\#xs)!(\text{length } xs))) \neq \text{None}$
 $\langle \text{proof} \rangle$

lemma *Seq-sound1* [*rule-format*]:
 $x \in \text{cptn-mod} \implies \forall s \ P. \ x \neq 0 = (\text{Some } (\text{Seq } P \ Q), s) \longrightarrow$
 $(\forall i < \text{length } x. \ \text{fst}(x!i) \neq \text{Some } Q) \longrightarrow$
 $(\exists xs \in \text{cp } (\text{Some } P) \ s. \ x = \text{map } (\text{lift } Q) \ xs)$
 $\langle \text{proof} \rangle$

lemma *Seq-sound2* [*rule-format*]:
 $x \in \text{cptn} \implies \forall s \ P \ i. \ x \neq 0 = (\text{Some } (\text{Seq } P \ Q), s) \longrightarrow i < \text{length } x$
 $\longrightarrow \text{fst}(x!i) = \text{Some } Q \longrightarrow$
 $(\forall j < i. \ \text{fst}(x!j) \neq (\text{Some } Q)) \longrightarrow$
 $(\exists xs \ ys. \ xs \in \text{cp } (\text{Some } P) \ s \wedge \text{length } xs = \text{Suc } i$
 $\wedge \ ys \in \text{cp } (\text{Some } Q) \ (\text{snd}(xs \ !i)) \wedge x = (\text{map } (\text{lift } Q) \ xs) @ \text{tl } ys)$
 $\langle \text{proof} \rangle$

lemma *last-lift-not-None2*: $\text{fst } ((\text{lift } Q) (\text{last } (x\#xs))) \neq \text{None}$
 $\langle \text{proof} \rangle$

lemma *Seq-sound*:
 $\llbracket \models P \ \text{sat } [\text{pre}, \ \text{rely}, \ \text{guar}, \ \text{mid}]; \models Q \ \text{sat } [\text{mid}, \ \text{rely}, \ \text{guar}, \ \text{post}] \rrbracket$
 $\implies \models \text{Seq } P \ Q \ \text{sat } [\text{pre}, \ \text{rely}, \ \text{guar}, \ \text{post}]$
 $\langle \text{proof} \rangle$

Soundness of the While rule

lemma *last-append* [*rule-format*]:
 $\forall xs. \ ys \neq [] \longrightarrow ((xs @ ys)!(\text{length } (xs @ ys) - (\text{Suc } 0))) = (ys!(\text{length } ys - (\text{Suc } 0)))$
 $\langle \text{proof} \rangle$

lemma *assum-after-body*:
 $\llbracket \models P \ \text{sat } [\text{pre} \cap b, \ \text{rely}, \ \text{guar}, \ \text{pre}];$
 $(\text{Some } P, s) \# xs \in \text{cptn-mod}; \text{fst } (\text{last } ((\text{Some } P, s) \# xs)) = \text{None}; s \in b;$
 $(\text{Some } (\text{While } b \ P), s) \# (\text{Some } (\text{Seq } P \ (\text{While } b \ P)), s) \#$
 $\text{map } (\text{lift } (\text{While } b \ P)) \ xs \ @ \ ys \in \text{assum } (\text{pre}, \ \text{rely}) \rrbracket$
 $\implies (\text{Some } (\text{While } b \ P), \text{snd } (\text{last } ((\text{Some } P, s) \# xs))) \# ys \in \text{assum } (\text{pre}, \ \text{rely})$
 $\langle \text{proof} \rangle$

lemma *While-sound-aux* [*rule-format*]:
 $\llbracket \text{pre} \cap \neg b \subseteq \text{post}; \models P \ \text{sat } [\text{pre} \cap b, \ \text{rely}, \ \text{guar}, \ \text{pre}]; \forall s. \ (s, s) \in \text{guar};$
 $\text{stable } \text{pre } \ \text{rely}; \ \text{stable } \text{post } \ \text{rely}; \ x \in \text{cptn-mod} \rrbracket$
 $\implies \forall s \ xs. \ x = (\text{Some } (\text{While } b \ P), s) \# xs \longrightarrow x \in \text{comm}(\text{pre}, \ \text{rely}) \longrightarrow x \in \text{comm}$
 $(\text{guar}, \ \text{post})$
 $\langle \text{proof} \rangle$

lemma *While-sound:*

$$\begin{aligned} & \llbracket \text{stable } pre \text{ rely}; pre \cap - b \subseteq post; \text{stable } post \text{ rely}; \\ & \quad \models P \text{ sat } [pre \cap b, \text{rely}, guar, pre]; \forall s. (s, s) \in guar \rrbracket \\ & \implies \models \text{While } b \text{ } P \text{ sat } [pre, \text{rely}, guar, post] \\ & \langle \text{proof} \rangle \end{aligned}$$

Soundness of the Rule of Consequence

lemma *Conseq-sound:*

$$\begin{aligned} & \llbracket pre \subseteq pre'; \text{rely} \subseteq \text{rely}'; guar' \subseteq guar; post' \subseteq post; \\ & \quad \models P \text{ sat } [pre', \text{rely}', guar', post'] \rrbracket \\ & \implies \models P \text{ sat } [pre, \text{rely}, guar, post] \\ & \langle \text{proof} \rangle \end{aligned}$$

Soundness of the system for sequential component programs

theorem *rgsound:*

$$\vdash P \text{ sat } [pre, \text{rely}, guar, post] \implies \models P \text{ sat } [pre, \text{rely}, guar, post]$$

$\langle \text{proof} \rangle$

3.5.2 Soundness of the System for Parallel Programs

definition *ParallelCom* :: ('a rgformula) list \Rightarrow 'a par-com **where**

$$\text{ParallelCom } Ps \equiv \text{map } (\text{Some} \circ \text{fst}) \text{ } Ps$$

lemma *two:*

$$\begin{aligned} & \llbracket \forall i < \text{length } xs. \text{rely} \cup (\bigcup j \in \{j. j < \text{length } xs \wedge j \neq i\}. \text{Guar } (xs ! j)) \\ & \quad \subseteq \text{Rely } (xs ! i); \\ & \quad pre \subseteq (\bigcap i \in \{i. i < \text{length } xs\}. \text{Pre } (xs ! i)); \\ & \quad \forall i < \text{length } xs. \\ & \quad \models \text{Com } (xs ! i) \text{ sat } [\text{Pre } (xs ! i), \text{Rely } (xs ! i), \text{Guar } (xs ! i), \text{Post } (xs ! i)]; \\ & \quad \text{length } xs = \text{length } \text{clist}; x \in \text{par-cp } (\text{ParallelCom } xs) \text{ } s; x \in \text{par-assum}(pre, \text{rely}); \\ & \quad \forall i < \text{length } \text{clist}. \text{clist} ! i \in \text{cp } (\text{Some}(\text{Com}(xs ! i))) \text{ } s; x \propto \text{clist} \rrbracket \\ & \implies \forall j \text{ } i. i < \text{length } \text{clist} \wedge \text{Suc } j < \text{length } x \longrightarrow (\text{clist} ! i ! j) -c \rightarrow (\text{clist} ! i ! \text{Suc } j) \\ & \longrightarrow (\text{snd}(\text{clist} ! i ! j), \text{snd}(\text{clist} ! i ! \text{Suc } j)) \in \text{Guar}(xs ! i) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *three [rule-format]:*

$$\begin{aligned} & \llbracket xs \neq []; \forall i < \text{length } xs. \text{rely} \cup (\bigcup j \in \{j. j < \text{length } xs \wedge j \neq i\}. \text{Guar } (xs ! j)) \\ & \quad \subseteq \text{Rely } (xs ! i); \\ & \quad pre \subseteq (\bigcap i \in \{i. i < \text{length } xs\}. \text{Pre } (xs ! i)); \\ & \quad \forall i < \text{length } xs. \\ & \quad \models \text{Com } (xs ! i) \text{ sat } [\text{Pre } (xs ! i), \text{Rely } (xs ! i), \text{Guar } (xs ! i), \text{Post } (xs ! i)]; \\ & \quad \text{length } xs = \text{length } \text{clist}; x \in \text{par-cp } (\text{ParallelCom } xs) \text{ } s; x \in \text{par-assum}(pre, \text{rely}); \\ & \quad \forall i < \text{length } \text{clist}. \text{clist} ! i \in \text{cp } (\text{Some}(\text{Com}(xs ! i))) \text{ } s; x \propto \text{clist} \rrbracket \\ & \implies \forall j \text{ } i. i < \text{length } \text{clist} \wedge \text{Suc } j < \text{length } x \longrightarrow (\text{clist} ! i ! j) -e \rightarrow (\text{clist} ! i ! \text{Suc } j) \\ & \longrightarrow (\text{snd}(\text{clist} ! i ! j), \text{snd}(\text{clist} ! i ! \text{Suc } j)) \in \text{rely} \cup (\bigcup j \in \{j. j < \text{length } xs \wedge j \neq i\}. \\ & \text{Guar } (xs ! j)) \end{aligned}$$

<proof>

lemma four:

$\llbracket xs \neq [] \rrbracket; \forall i < \text{length } xs. \text{rely} \cup (\bigcup j \in \{j. j < \text{length } xs \wedge j \neq i\}. \text{Guar } (xs ! j))$
 $\subseteq \text{Rely } (xs ! i);$
 $(\bigcup j \in \{j. j < \text{length } xs\}. \text{Guar } (xs ! j)) \subseteq \text{guar};$
 $\text{pre} \subseteq (\bigcap i \in \{i. i < \text{length } xs\}. \text{Pre } (xs ! i));$
 $\forall i < \text{length } xs.$
 $\models \text{Com } (xs ! i) \text{ sat } [\text{Pre } (xs ! i), \text{Rely } (xs ! i), \text{Guar } (xs ! i), \text{Post } (xs ! i)];$
 $x \in \text{par-cp } (\text{ParallelCom } xs) \text{ s}; x \in \text{par-assum } (\text{pre}, \text{rely}); \text{Suc } i < \text{length } x;$
 $x ! i \text{ -pc} \rightarrow x ! \text{Suc } i \rrbracket$
 $\implies (\text{snd } (x ! i), \text{snd } (x ! \text{Suc } i)) \in \text{guar}$

<proof>

lemma parcptn-not-empty [simp]: $\llbracket \rrbracket \notin \text{par-cptn}$

<proof>

lemma five:

$\llbracket xs \neq [] \rrbracket; \forall i < \text{length } xs. \text{rely} \cup (\bigcup j \in \{j. j < \text{length } xs \wedge j \neq i\}. \text{Guar } (xs ! j))$
 $\subseteq \text{Rely } (xs ! i);$
 $\text{pre} \subseteq (\bigcap i \in \{i. i < \text{length } xs\}. \text{Pre } (xs ! i));$
 $(\bigcap i \in \{i. i < \text{length } xs\}. \text{Post } (xs ! i)) \subseteq \text{post};$
 $\forall i < \text{length } xs.$
 $\models \text{Com } (xs ! i) \text{ sat } [\text{Pre } (xs ! i), \text{Rely } (xs ! i), \text{Guar } (xs ! i), \text{Post } (xs ! i)];$
 $x \in \text{par-cp } (\text{ParallelCom } xs) \text{ s}; x \in \text{par-assum } (\text{pre}, \text{rely});$
 $\text{All-None } (\text{fst } (\text{last } x)) \rrbracket \implies \text{snd } (\text{last } x) \in \text{post}$

<proof>

lemma ParallelEmpty [rule-format]:

$\forall i \text{ s. } x \in \text{par-cp } (\text{ParallelCom } []) \text{ s} \longrightarrow$
 $\text{Suc } i < \text{length } x \longrightarrow (x ! i, x ! \text{Suc } i) \notin \text{par-ctran}$

<proof>

theorem par-rgsound:

$\vdash c \text{ SAT } [\text{pre}, \text{rely}, \text{guar}, \text{post}] \implies$
 $\models (\text{ParallelCom } c) \text{ SAT } [\text{pre}, \text{rely}, \text{guar}, \text{post}]$

<proof>

end

3.6 Concrete Syntax

theory *RG-Syntax*

imports *RG-Hoare Quote-Antiquote*

begin

abbreviation *Skip* $:: 'a \text{ com } (\langle \text{SKIP} \rangle)$

where *SKIP* $\equiv \text{Basic id}$

notation *Seq* $\langle (-; / -) \rangle$ [60,61] 60)

syntax

-Assign :: $idt \Rightarrow 'b \Rightarrow 'a \text{ com}$ $\langle (' - := / -) \rangle$ [70, 65] 61)
 -Cond :: $'a \text{ bexp} \Rightarrow 'a \text{ com} \Rightarrow 'a \text{ com} \Rightarrow 'a \text{ com}$ $\langle (0IF - / THEN - / ELSE - / FI) \rangle$ [0, 0, 0] 61)
 -Cond2 :: $'a \text{ bexp} \Rightarrow 'a \text{ com} \Rightarrow 'a \text{ com}$ $\langle (0IF - THEN - FI) \rangle$ [0,0] 56)
 -While :: $'a \text{ bexp} \Rightarrow 'a \text{ com} \Rightarrow 'a \text{ com}$ $\langle (0WHILE - / DO - / OD) \rangle$ [0, 0] 61)
 -Await :: $'a \text{ bexp} \Rightarrow 'a \text{ com} \Rightarrow 'a \text{ com}$ $\langle (0AWAIT - / THEN - / END) \rangle$ [0,0] 61)
 -Atom :: $'a \text{ com} \Rightarrow 'a \text{ com}$ $\langle ((-) \rangle$ 61)
 -Wait :: $'a \text{ bexp} \Rightarrow 'a \text{ com}$ $\langle (0WAIT - END) \rangle$ 61)

translations

$'x := a \rightarrow \text{CONST Basic} \langle '(-\text{update-name } x (\lambda-. a)) \rangle$
 $IF b THEN c1 ELSE c2 FI \rightarrow \text{CONST Cond} \{b\} c1 c2$
 $IF b THEN c FI \Leftrightarrow IF b THEN c ELSE SKIP FI$
 $WHILE b DO c OD \rightarrow \text{CONST While} \{b\} c$
 $AWAIT b THEN c END \Leftrightarrow \text{CONST Await} \{b\} c$
 $\langle c \rangle \Leftrightarrow \text{AWAIT CONST True THEN } c \text{ END}$
 $WAIT b END \Leftrightarrow \text{AWAIT } b \text{ THEN SKIP END}$

nonterminal *prgs*

syntax

-PAR :: $prgs \Rightarrow 'a$ $\langle (COBEGIN // - // COEND) \rangle$ 60)
 -prg :: $'a \Rightarrow prgs$ $\langle (-) \rangle$ 57)
 -prgs :: $['a, prgs] \Rightarrow prgs$ $\langle (- // || // -) \rangle$ [60,57] 57)

translations

-prg $a \rightarrow [a]$
 -prgs $a \text{ ps} \rightarrow a \# \text{ ps}$
 -PAR $ps \rightarrow ps$

syntax

-prg-scheme :: $['a, 'a, 'a, 'a] \Rightarrow prgs$ $\langle (SCHEME [- \leq - < -] -) \rangle$ [0,0,0,60] 57)

translations

-prg-scheme $j \ i \ k \ c \Leftrightarrow (\text{CONST map } (\lambda i. c) [j..<k])$

Translations for variables before and after a transition:

syntax

-before :: $id \Rightarrow 'a \langle (-^{\circ}) \rangle$
 -after :: $id \Rightarrow 'a \langle (-^{\text{a}}) \rangle$

translations

${}^{\circ}x \Leftrightarrow x \ ' \text{CONST } fst$

$\text{a}x \rightleftharpoons x \text{ ' } \text{CONST } \text{snd}$

$\langle \text{ML} \rangle$

end

3.7 Examples

theory *RG-Examples*

imports *RG-Syntax*

begin

lemmas *definitions* [*simp*]= *stable-def Pre-def Rely-def Guar-def Post-def Com-def*

3.7.1 Set Elements of an Array to Zero

lemma *le-less-trans2*: $\llbracket (j::\text{nat}) < k; i \leq j \rrbracket \implies i < k$

$\langle \text{proof} \rangle$

lemma *add-le-less-mono*: $\llbracket (a::\text{nat}) < c; b \leq d \rrbracket \implies a + b < c + d$

$\langle \text{proof} \rangle$

record *Example1* =

A :: *nat list*

lemma *Example1*:

$\vdash \text{COBEGIN}$

SCHEME $[0 \leq i < n]$

$(\text{' } A := \text{' } A [i := 0]),$

$\{\!| n < \text{length } \text{' } A \!\!\},$

$\{\!| \text{length } \text{a}A = \text{length } \text{a}A \wedge \text{a}A ! i = \text{a}A ! i \!\!\},$

$\{\!| \text{length } \text{a}A = \text{length } \text{a}A \wedge (\forall j < n. i \neq j \longrightarrow \text{a}A ! j = \text{a}A ! j) \!\!\},$

$\{\!| \text{' } A ! i = 0 \!\!\}$

COEND

SAT $\{\!| n < \text{length } \text{' } A \!\!\}, \{\!| \text{a}A = \text{a}A \!\!\}, \{\!| \text{True} \!\!\}, \{\!| \forall i < n. \text{' } A ! i = 0 \!\!\}$

$\langle \text{proof} \rangle$

lemma *Example1-parameterized*:

$k < t \implies$

$\vdash \text{COBEGIN}$

SCHEME $[k * n \leq i < (\text{Suc } k) * n] (\text{' } A := \text{' } A [i := 0]),$

$\{\!| t * n < \text{length } \text{' } A \!\!\},$

$\{\!| t * n < \text{length } \text{a}A \wedge \text{length } \text{a}A = \text{length } \text{a}A \wedge \text{a}A ! i = \text{a}A ! i \!\!\},$

$\{\!| t * n < \text{length } \text{a}A \wedge \text{length } \text{a}A = \text{length } \text{a}A \wedge (\forall j < \text{length } \text{a}A. i \neq j \longrightarrow \text{a}A ! j = \text{a}A ! j) \!\!\},$

$\{\!| \text{' } A ! i = 0 \!\!\}$

COEND

SAT $\{\!| t * n < \text{length } \text{' } A \!\!\},$

$\{\!| t * n < \text{length } \text{a}A \wedge \text{length } \text{a}A = \text{length } \text{a}A \wedge (\forall i < n. \text{a}A ! (k * n + i) = \text{a}A ! (k * n + i)) \!\!\},$

$$\{ \{ t * n < \text{length } {}^{\circ}A \wedge \text{length } {}^{\circ}A = \text{length } {}^{\text{a}}A \wedge$$

$$(\forall i < \text{length } {}^{\circ}A . (i < k * n \longrightarrow {}^{\circ}A!i = {}^{\text{a}}A!i) \wedge ((\text{Suc } k) * n \leq i \longrightarrow {}^{\circ}A!i = {}^{\text{a}}A!i)) \},$$

$$\{ \forall i < n . {}^{\text{a}}A!(k * n + i) = 0 \}$$

<proof>

3.7.2 Increment a Variable in Parallel

Two components

record *Example2* =

x :: nat
c-0 :: nat
c-1 :: nat

lemma *Example2*:

⊢ *COBEGIN*

$$(\langle \text{' } x := \text{' } x + 1;; \text{' } c-0 := \text{' } c-0 + 1 \rangle,$$

$$\{ \text{' } x = \text{' } c-0 + \text{' } c-1 \wedge \text{' } c-0 = 0 \},$$

$$\{ {}^{\circ}c-0 = {}^{\text{a}}c-0 \wedge$$

$$({}^{\circ}x = {}^{\circ}c-0 + {}^{\circ}c-1$$

$$\longrightarrow {}^{\text{a}}x = {}^{\text{a}}c-0 + {}^{\text{a}}c-1) \},$$

$$\{ {}^{\circ}c-1 = {}^{\text{a}}c-1 \wedge$$

$$({}^{\circ}x = {}^{\circ}c-0 + {}^{\circ}c-1$$

$$\longrightarrow {}^{\text{a}}x = {}^{\text{a}}c-0 + {}^{\text{a}}c-1) \},$$

$$\{ \text{' } x = \text{' } c-0 + \text{' } c-1 \wedge \text{' } c-0 = 1 \})$$

||

$$(\langle \text{' } x := \text{' } x + 1;; \text{' } c-1 := \text{' } c-1 + 1 \rangle,$$

$$\{ \text{' } x = \text{' } c-0 + \text{' } c-1 \wedge \text{' } c-1 = 0 \},$$

$$\{ {}^{\circ}c-1 = {}^{\text{a}}c-1 \wedge$$

$$({}^{\circ}x = {}^{\circ}c-0 + {}^{\circ}c-1$$

$$\longrightarrow {}^{\text{a}}x = {}^{\text{a}}c-0 + {}^{\text{a}}c-1) \},$$

$$\{ {}^{\circ}c-0 = {}^{\text{a}}c-0 \wedge$$

$$({}^{\circ}x = {}^{\circ}c-0 + {}^{\circ}c-1$$

$$\longrightarrow {}^{\text{a}}x = {}^{\text{a}}c-0 + {}^{\text{a}}c-1) \},$$

$$\{ \text{' } x = \text{' } c-0 + \text{' } c-1 \wedge \text{' } c-1 = 1 \})$$

COEND

SAT [$\{ \text{' } x = 0 \wedge \text{' } c-0 = 0 \wedge \text{' } c-1 = 0 \},$
 $\{ {}^{\circ}x = {}^{\text{a}}x \wedge {}^{\circ}c-0 = {}^{\text{a}}c-0 \wedge {}^{\circ}c-1 = {}^{\text{a}}c-1 \},$
 $\{ \text{True} \},$
 $\{ \text{' } x = 2 \}]$

<proof>

Parameterized

lemma *Example2-lemma2-aux*: $j < n \implies$
 $(\sum i = 0 .. < n . (b \ i :: \text{nat})) =$
 $(\sum i = 0 .. < j . b \ i) + b \ j + (\sum i = 0 .. < n - (\text{Suc } j) . b \ (\text{Suc } j + i))$

<proof>

lemma *Example2-lemma2-aux2*:

$j \leq s \implies (\sum i::\text{nat}=0..<j. (b (s:=t)) i) = (\sum i=0..<j. b i)$
 ⟨proof⟩

lemma *Example2-lemma2*:

$\llbracket j < n; b j = 0 \rrbracket \implies \text{Suc} (\sum i::\text{nat}=0..<n. b i) = (\sum i=0..<n. (b (j := \text{Suc } 0)) i)$
 ⟨proof⟩

lemma *Example2-lemma2-Suc0*: $\llbracket j < n; b j = 0 \rrbracket \implies$

$\text{Suc} (\sum i::\text{nat}=0..<n. b i) = (\sum i=0..<n. (b (j := \text{Suc } 0)) i)$
 ⟨proof⟩

record *Example2-parameterized* =

$C :: \text{nat} \Rightarrow \text{nat}$
 $y :: \text{nat}$

lemma *Example2-parameterized*: $0 < n \implies$

$\vdash \text{COBEGIN SCHEME } [0 \leq i < n]$
 $(\langle \text{' } y := \text{' } y + 1;; \text{' } C := \text{' } C (i := 1) \rangle,$
 $\{\text{' } y = (\sum i=0..<n. \text{' } C i) \wedge \text{' } C i = 0\},$
 $\{\text{' } C i = \text{' } C i \wedge$
 $(\text{' } y = (\sum i=0..<n. \text{' } C i) \longrightarrow \text{' } y = (\sum i=0..<n. \text{' } C i))\},$
 $\{\forall j < n. i \neq j \longrightarrow \text{' } C j = \text{' } C i \wedge$
 $(\text{' } y = (\sum i=0..<n. \text{' } C i) \longrightarrow \text{' } y = (\sum i=0..<n. \text{' } C i))\},$
 $\{\text{' } y = (\sum i=0..<n. \text{' } C i) \wedge \text{' } C i = 1\})$
 COEND
 $\text{SAT } [\{\text{' } y = 0 \wedge (\sum i=0..<n. \text{' } C i) = 0\}, \{\text{' } C = \text{' } C \wedge \text{' } y = \text{' } y\}, \{\text{True}\}, \{\text{' } y = n\}]$
 ⟨proof⟩

3.7.3 Find Least Element

A previous lemma:

lemma *mod-aux*: $\llbracket i < (n::\text{nat}); a \bmod n = i; j < a + n; j \bmod n = i; a < j \rrbracket \implies$
 False
 ⟨proof⟩

record *Example3* =

$X :: \text{nat} \Rightarrow \text{nat}$
 $Y :: \text{nat} \Rightarrow \text{nat}$

lemma *Example3*: $m \bmod n = 0 \implies$

$\vdash \text{COBEGIN}$
 $\text{SCHEME } [0 \leq i < n]$
 $(\text{WHILE } (\forall j < n. \text{' } X i < \text{' } Y j) \text{ DO}$
 $\text{IF } P(B!(\text{' } X i)) \text{ THEN } \text{' } Y := \text{' } Y (i := \text{' } X i)$
 $\text{ELSE } \text{' } X := \text{' } X (i := (\text{' } X i) + n) \text{ FI}$
 $\text{OD},$
 $\{\text{' } X i \bmod n = i \wedge (\forall j < \text{' } X i. j \bmod n = i \longrightarrow \neg P(B!j)) \wedge (\text{' } Y i < m \longrightarrow P(B!(\text{' } Y$
 $i)) \wedge \text{' } Y i \leq m + i)\},$
 $\{\forall j < n. i \neq j \longrightarrow \text{' } Y j \leq \text{' } Y i \wedge \text{' } X i = \text{' } X i \wedge$

$\circ Y\ i = \text{a}Y\ i\},$
 $\{\{\forall j < n. i \neq j \longrightarrow \circ X\ j = \text{a}X\ j \wedge \circ Y\ j = \text{a}Y\ j\} \wedge$
 $\text{a}Y\ i \leq \circ Y\ i\},$
 $\{\{\text{' }X\ i\} \bmod n = i \wedge (\forall j < \text{' }X\ i. j \bmod n = i \longrightarrow \neg P(B!j)) \wedge (\text{' }Y\ i < m \longrightarrow P(B!(\text{' }Y\ i))) \wedge \text{' }Y\ i \leq m+i\} \wedge (\exists j < n. \text{' }Y\ j \leq \text{' }X\ i)\ \}\}$
COEND
SAT $[\{\{\forall i < n. \text{' }X\ i = i \wedge \text{' }Y\ i = m+i\}, \{\circ X = \text{a}X \wedge \circ Y = \text{a}Y\}, \{\text{True}\},$
 $\{\{\forall i < n. (\text{' }X\ i\} \bmod n = i \wedge (\forall j < \text{' }X\ i. j \bmod n = i \longrightarrow \neg P(B!j)) \wedge$
 $(\text{' }Y\ i < m \longrightarrow P(B!(\text{' }Y\ i))) \wedge \text{' }Y\ i \leq m+i\} \wedge (\exists j < n. \text{' }Y\ j \leq \text{' }X\ i)\ \}\}$
 $\langle \text{proof} \rangle$

Same but with a list as auxiliary variable:

record *Example3-list* =
 $X :: \text{nat list}$
 $Y :: \text{nat list}$

lemma *Example3-list*: $m \bmod n = 0 \implies \vdash (\text{COBEGIN SCHEME } [0 \leq i < n]$
 $(\text{WHILE } (\forall j < n. \text{' }X!i < \text{' }Y!j) \text{ DO}$
 $\text{IF } P(B!(\text{' }X!i)) \text{ THEN } \text{' }Y := \text{' }Y[i := \text{' }X!i] \text{ ELSE } \text{' }X := \text{' }X[i := (\text{' }X!i) + n] \text{ FI}$
 $\text{OD},$
 $\{\{n < \text{length } \text{' }X \wedge n < \text{length } \text{' }Y \wedge (\text{' }X!i) \bmod n = i \wedge (\forall j < \text{' }X!i. j \bmod n = i \longrightarrow$
 $\neg P(B!j)) \wedge (\text{' }Y!i < m \longrightarrow P(B!(\text{' }Y!i))) \wedge \text{' }Y!i \leq m+i\}\},$
 $\{\{\forall j < n. i \neq j \longrightarrow \text{a}Y!j \leq \circ Y!j\} \wedge \circ X!i = \text{a}X!i \wedge$
 $\circ Y!i = \text{a}Y!i \wedge \text{length } \circ X = \text{length } \text{a}X \wedge \text{length } \circ Y = \text{length } \text{a}Y\},$
 $\{\{\forall j < n. i \neq j \longrightarrow \circ X!j = \text{a}X!j \wedge \circ Y!j = \text{a}Y!j\} \wedge$
 $\text{a}Y!i \leq \circ Y!i \wedge \text{length } \circ X = \text{length } \text{a}X \wedge \text{length } \circ Y = \text{length } \text{a}Y\},$
 $\{\{\text{' }X!i\} \bmod n = i \wedge (\forall j < \text{' }X!i. j \bmod n = i \longrightarrow \neg P(B!j)) \wedge (\text{' }Y!i < m \longrightarrow P(B!(\text{' }Y!i)))$
 $\wedge \text{' }Y!i \leq m+i\} \wedge (\exists j < n. \text{' }Y!j \leq \text{' }X!i)\ \}\} \text{ COEND}$
SAT $[\{\{n < \text{length } \text{' }X \wedge n < \text{length } \text{' }Y \wedge (\forall i < n. \text{' }X!i = i \wedge \text{' }Y!i = m+i)\ \},$
 $\{\circ X = \text{a}X \wedge \circ Y = \text{a}Y\},$
 $\{\text{True}\},$
 $\{\{\forall i < n. (\text{' }X!i) \bmod n = i \wedge (\forall j < \text{' }X!i. j \bmod n = i \longrightarrow \neg P(B!j)) \wedge$
 $(\text{' }Y!i < m \longrightarrow P(B!(\text{' }Y!i))) \wedge \text{' }Y!i \leq m+i\} \wedge (\exists j < n. \text{' }Y!j \leq \text{' }X!i)\ \}\}$
 $\langle \text{proof} \rangle$

end
theory *Hoare-Parallel*
imports *OG-Examples Gar-Coll Mul-Gar-Coll RG-Examples*
begin

end

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