

Formal Theory of Communication Topology in Concurrent ML

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1 Mathematical Artifacts

```
1  type thread_id
2  val spawn : (unit -> unit) -> thread_id
3
4  type 'a chan
5  val channel : unit -> 'a chan
6  val recv : 'a chan -> 'a
7  val send : ('a chan * 'a) -> unit
8
9
10
11 signature SERV = sig
12   type serv
13   val make : unit -> serv
14   val call : serv * int -> int
15 end
16
17 structure Serv : SERV = struct
18   datatype serv = S of (int * int chan) chan
19
20   fun make () = let
21     val reqChn = channel ()
22     fun loop state = let
23       val (v, replCh) = recv reqChn in
24       send (replCh, state);
25       loop v end in
26     spawn (fn () => loop 0);
27     S reqChn end
28
29   fun call (server, v) = let
30     val S reqChn = server
31     val replChn = channel () in
32     send (reqCh, (v, replCh));
33     recv replChn end end
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```

```

12
13

1  val server = Serv.make ()
2  val _ = spawn (fn () => Serv.call (server, 35))
3  val _ = spawn (fn () =>
4      Serv.call (server, 12);
5      Serv.call (server, 13))
6  val _ = spawn (fn () => Serv.call (server, 81))
7  val _ = spawn (fn () => Serv.call (server, 44))
8

1  structure Serv : SERV = struct
2      datatype serv = S of (int * int chan) chan
3
4      fun make () = let
5
6          val reqChn = FanIn.channel()
7
8          fun loop state = let
9              val (v, replCh) = FanIn.recv reqChn in
10                 OneShot.send (replCh, state);
11                 loop v end in
12
13             spawn (fn () => loop 0);
14             S reqChn end
15
16     fun call (server, v) = let
17         val S reqChn = server
18         val replChn = OneShot.channel () in
19             FanIn.send (reqCh, (v, replCh));
20             OneShot.recv replChn end
21
22     end
23

1  let
2      val w = 4
3      val x = ref 1
4      val y = ref 2
5      val z = (!x + 1) + (!y + 2) + (w - 3)
6      val w = 1 in
7          y := 0;
8          (!y + 2) - (!x + 1) * (w - 3) end
9

1  let
2      val x = 1
3      val y = 2
4      val z = ref (4 * 73)

```

```

5     val x = 4 in
6     z := 1;
7     x * !z end
8
1
2   let
3     val f = fn x => x 1
4     val g = fn y => y + 2
5     val h = fn z => z + 3 in
6     (f g) + (f h) end
7
1
2   datatype 'a list = Nil | Cons 'a ('a list)
3
4   inductive sorted : :
5     ('a => 'a => bool) =>
6     'a list => bool where
7     Nil : sorted P Nil |
8     Single : sorted P (Cons x Nil) |
9     Cons :
10      P x y =>
11      sorted P (Cons y ys) =>
12      sorted P (Cons x (Cons y ys))
13
1
2   datatype nat = Z | S nat
3
4   inductive lte : : nat => nat => bool where
5     Eq : lte n n |
6     Lt : lte n1 n2 => lte n1 (S n2)
7
8   theorem "
9     sorted lte
10      (Cons (Z) (Cons (S Z)
11        (Cons (S Z) (Cons
12          (S (S (S Z))) Nil))))"
13   apply (rule Cons)
14   apply (rule Lt)
15   apply (rule Eq)
16   apply (rule Cons)
17   apply (rule Eq)
18   apply (rule Cons)
19   apply (rule Lt)
20   apply (rule Lt)
21   apply (rule Eq)
22   apply (rule Single)
23   done

```

```

1  definition True : : bool where
2    True  $\equiv$  (( $\lambda x$  : : bool. x) = ( $\lambda x$ . x))
3
4  definition False : : bool where
5    False  $\equiv$  ( $\forall P$ . P)
6
7
1
2  signature CHAN = sig
3    type 'a chan
4    val channel : unit -> 'a chan
5    val send : 'a chan * 'a -> unit
6    val recv : 'a chan -> 'a
7  end
8
9
10 structure ManyToManyChan : CHAN = struct
11   type message_queue = 'a option ref queue
12
13   datatype 'a chan_content =
14     Send of (condition * 'a) queue |
15     Recv of (condition * 'a option ref) queue |
16     Inac
17
18   datatype 'a chan =
19     Chn of 'a chan_content ref * mutex_lock
20
21   fun channel () = Chn (ref Inac, mutexLock ())
22
23   fun send (Chn (conRef, lock)) m =
24     acquire lock;
25     (case !conRef of
26       Recv q => let
27         val (recvCond, mopRef) = dequeue q in
28         mopRef := Some m;
29         if (isEmpty q) then conRef := Inac else ();
30         release lock; signal recvCond; () end |
31       Send q => let
32         val sendCond = condition () in
33         enqueue (q, (sendCond, m));
34         release lock; wait sendCond; () end |
35       Inac => let
36         val sendCond = condition () in
37         conRef := Send (queue [(sendCond, m)]);
38         release lock; wait sendCond; () end)
39
40   fun recv (Chn (conRef, lock)) =
41     acquire lock;
42     (case !conRef of
43       Send q => let

```

```

36         val (sendCond, m) = dequeue q in
37         if (isEmpty q) then
38             conRef := Inac
39         else
40             ();
41         release lock; signal sendCond; m end |
42     Recv q => let
43         val recvCond = condition ()
44         val mopRef = ref None in
45         enqueue (q, (recvCond, mopRef));
46         release lock; wait recvCond;
47         valOf (!mopRef) end |
48     Inac => let
49         val recvCond = condition ()
50         val mopRef = ref None in
51         conRef := Recv (queue [(recvCond, mopRef)]);
52         release lock; wait recvCond;
53         valOf (!mopRef) end)
54
55 end
56
57
1
2 structure FanOutChan : CHAN = struct
3
4 datatype 'a chan_content =
5     Send of condition * 'a |
6     Recv of (condition * 'a option ref) queue |
7     Inac
8
9 datatype 'a chan =
10     Chn of 'a chan_content ref * mutex_lock
11
12 fun channel () = Chn (ref Inac, mutexLock ())
13
14 fun send (Chn (conRef, lock)) m = let
15     val sendCond = condition () in
16     case cas (conRef, Inac, Send (sendCond, m)) of
17         Inac => (* conRef already set *)
18             wait sendCond; () |
19         Recv q =>
20             (* the current thread is
21              * the only one that updates from this state *)
22             acquire lock;
23             (let
24                 val (recvCond, mopRef) = dequeue q in
25                 mopRef := Some m;
26                 if (isEmpty q) then conRef := Inac else ();
27                 release lock; signal (recvCond);

```

```

28         () end) |
29         Send _ => raise NeverHappens end
30
31     fun recv (Chn (conRef, lock)) =
32         acquire lock;
33         (case !conRef of
34             Inac => let
35                 val recvCond = condition ()
36                 val mopRef = ref None in
37                 conRef := Recv (queue [(recvCond, mopRef)]);
38                 release lock; wait recvCond;
39                 valOf (!mopRef) end |
40             Recv q => let
41                 val recvCond = condition ()
42                 val mopRef = ref None in
43                 enqueue (q, (recvCond, mopRef));
44                 release lock; wait recvCond;
45                 valOf (!mopRef) end |
46             Send (sendCond, m) =>
47                 conRef := Inac;
48                 release lock;
49                 signal sendCond;
50                 m end)
51
52     end
53
54
55 1  structure FanInChan : CHAN = struct
56 2
57 3  datatype 'a chan_content =
58 4      Send of (condition * 'a) queue |
59 5      Recv of condition * 'a option ref |
60 6      Inac
61 7
62 8  datatype 'a chan =
63 9      Chn of 'a chan_content ref * mutex_lock
64 10
65 11 fun channel () = Chn (ref Inac, mutexLock ())
66 12
67 13 fun send (Chn (conRef, lock)) m =
68 14     acquire lock;
69 15     case !conRef of
70 16     Recv (recvCond, mopRef) =>
71 17         mopRef := Some m; conRef := Inac;
72 18         release lock; signal recvCond;
73 19         () |
74 20     Send q => let
75 21         val sendCond = condition () in
76 22         enqueue (q, (sendCond, m));
77 23         release lock; wait sendCond;

```

```

24     () end |
25   Inac => let
26     val sendCond = condition () in
27     conRef := Send (queue [(sendCond, m)])
28     release lock; wait sendCond; () end
29
30 fun recv (Chn (conRef, lock)) = let
31   val recvCond = condition ()
32   val mopRef = ref None in
33   case cas (conRef, Inac, Recv (recvCond, mopRef)) of
34     Inac => (* conRef already set *)
35       wait recvCond; valOf (!mopRef) |
36     Send q =>
37       (* the current thread is the only one
38        * that updates the state from this state *)
39       acquire lock;
40       (let
41         val (sendCond, m) = dequeue q in
42         if (isEmpty q) then conRef := Inac else ();
43         release lock; signal sendCond; m end) |
44     Recv _ => raise NeverHappens end end
45
46

```

```

1
2 structure OneToOneChan : CHAN = struct
3
4   datatype 'a chan_content =
5     Send of condition * 'a |
6     Recv of condition * 'a option ref |
7     Inac
8
9   datatype 'a chan = Chn of 'a chan_content ref
10
11 fun channel () = Chn (ref Inac)
12
13 fun send (Chn conRef) m = let
14   val sendCond = condition () in
15   case cas (conRef, Inac, Send (sendCond, m)) of
16     Inac =>
17       (* conRef already set to Send *)
18       wait sendCond; () |
19     Recv (recvCond, mopRef) =>
20       (* the current thread is the only one
21        * that accesses conRef for this state *)
22       mopRef := Some m; conRef := Inac;
23       signal recvCond; () |
24     Send _ => raise NeverHappens end end
25
26

```



```

27 fun recv (Chn conRef) = let
28   val recvCond = condition ();
29   val mopRef = ref None in
30   case cas (conRef, Inac, Recv (recvCond, mopRef)) of
31     Inac => (* conRef already set to Recv*)
32       wait recvCond; valOf (!mopRef) |
33     Send (sendCond, m) =>
34       (* the current thread is the only one
35        * that accesses conRef for this state *)
36       conRef := Inac; signal sendCond; m |
37     Recv _ => raise NeverHappens end end
38
39 end
40
1  structure OneShotChan : CHAN = struct
2
3  datatype 'a chan_content =
4    Send of condition * 'a |
5    Recv of condition * 'a option ref |
6    Inac
7
8  datatype 'a chan = Chn of 'a chan_content ref * mutex_lock
9
10 fun channel () = Chn (ref Inac, lock ())
11
12 fun send (Chn (conRef, lock)) m = let
13   val sendCond = condition () in
14   case (conRef, Inac, Send (sendCond, m)) of
15     Inac =>
16       (* conRef already set to Send*)
17       wait sendCond; () |
18     Recv (recvCond, mopRef) =>
19       mopRef := Some m; signal recvCond;
20     () |
21     Send _ => raise NeverHappens end end
22
23
24 fun recv (Chn (conRef, lock)) = let
25   val recvCond = condition ()
26   val mopRef = ref None in
27   case (conRef, Inac, Recv (recvCond, mopRef)) of
28     Inac =>
29       (* conRef already set to Recv*)
30       wait recvCond; valOf (!mopRef) |
31     Send (sendCond, m) =>
32       acquire lock; signal sendCond;
33       (* never releases lock;
34        * blocks others forever *)
35     m |

```

```

36     Recv _ =>
37         acquire lock;
38         (* never able to acquire lock;
39         -* blocked forever *)
40         raise NeverHappens end end
41
42 end
43
1 structure OneShotToOneChan : CHAN = struct
2
3     datatype 'a chan =
4         Chn of condition * condition * 'a option ref
5
6     fun channel () =
7         Chn (condition (), condition (), ref None)
8
9     fun send (Chn (sendCond, recvCond, mopRef)) m =
10         mopRef := Some m; signal recvCond;
11         wait sendCond; ()
12
13     fun recv (Chn (sendCond, recvCond, mopRef)) =
14         wait recvCond; signal sendCond;
15         valOf (!mopRef)
16
17 end
18

```

2 Syntax

```

1
2     datatype var = Var string
3
4     datatype exp =
5         Let var boundexp exp |
6         Rslt var
7
8     boundexp =
9         Unt |
10        MkChn |
11        Prim prim |
12        Spwn exp |
13        Sync var |
14        Fst var |
15        Snd var |
16        Case var var exp var exp |
17        App var var and
18
19     prim =

```

```

20   SendEvt var var |
21   RecvEvt var |
22   Pair var var |
23   Lft var |
24   Rht var |
25   Abs var var ex

```

3 Dynamic Semantics

```

1  datatype ctrl_label =
2    LNxt var | LSpwn var | LCall var | LRtn var
3
4  type_synonym ctrl_path = (ctrl_label list)
5
6  datatype chan = Chn ctrl_path var
7
8  datatype val =
9    VUnt | VChn chan | VClsr prim (var  $\rightarrow$  val)
10
11  datatype ctn = Ctn var exp (var  $\rightarrow$  val)
12
13  datatype state = Stt exp (var  $\rightarrow$  val) (ctn list)
14
15

```

```

1
2  inductive seq_step : :
3    bind * (var  $\rightarrow$  val))  $\Rightarrow$  val  $\Rightarrow$  bool where
4    LetUnt :
5      seq_step (Unt, env) VUnt |
6    LetPrim :
7      seq_step (Prim p, env) (VClsr p env) |
8    LetFst :
9      env xp = Some (VClsr (Pair x1 x2) envp)  $\Rightarrow$ 
10      envp x1 = Some v  $\Rightarrow$ 
11      seq_step (Fst xp, env) v |
12    LetSnd :
13      env xp = Some (VClsr (Pair x1 x2) envp)  $\Rightarrow$ 
14      envp x2 = Some v  $\Rightarrow$ 
15      seq_step (Snd xp, env) v
16
17
18

```

```

1
2
3  inductive seq_step_up : :
4    bind * (var  $\rightarrow$  val))  $\Rightarrow$  exp * val_env  $\Rightarrow$  bool where
5    LetCaseLft :

```

```

6      env xs = Some (VClsr (Lft xl') envl) ==>
7      envl xl' = Some vl ==>
8      seq_step_up
9      (Case xs xl el xr er, env)
10     (el, env(xl ↦ vl)) |
11  LetCaseRht :
12     env xs = Some (VClsr (Rht xr') envr) ==>
13     envr xr' = Some vr ==>
14     seq_step_up
15     (Case xs xl el xr er, env)
16     (er, env(xr ↦ vr)) |
17  LetApp :
18     env f = Some (VClsr (Abs fp xp el) envl) ==>
19     env xa = Some va ==>
20     seq_step_up
21     (App f xa, env)
22     (el, envl(
23       fp ↦ (VClsr (Abs fp xp el) envl),
24       xp ↦ va))
25
1
2
3  type_synonym cmmn_set = (ctrl_path * chan * ctrl_path) set
4
5  type_synonym trace_pool = ctrl_path → state
6
7  inductive leaf : :
8    trace_pool ⇒ ctrl_path ⇒ bool where
9    intro :
10      trpl pi ≠ None ==>
11      (∄ pi' . trpl pi' ≠ None ∧ strict_prefix pi pi') ==>
12      leaf trpl pi
13
14
1
2  inductive concur_step : :
3    trace_pool * cmmn_set ⇒
4    trace_pool * cmmn_set ⇒
5    bool where
6    Seq_Ststep_Down :
7      leaf trpl pi ==>
8      trpl pi = Some
9      (Stt (Rslt x) env
10       ((Ctn xk ek envk) # k)) ==>
11      env x = Some v ==>
12      concur_step
13      (trpl, ys)

```

```

14      (trpl(pi @ [LRtn xk]  $\mapsto$ 
15        (Stt ek (envk(xk  $\mapsto$  v)) k)), ys) |
16 Seq_Step :
17   leaf trpl pi  $\Rightarrow$ 
18   trpl pi = Some
19     (Stt (Let x b e) env k)  $\Rightarrow$ 
20   seq_step (b, env) v  $\Rightarrow$ 
21   concur_step
22     (trpl, ys)
23     (trpl(pi @ [LNxt x]  $\mapsto$ 
24       (Stt e (env(x  $\mapsto$  v)) k)), ys) |
25 Seq_Step_Up :
26   leaf trpl pi  $\Rightarrow$ 
27   trpl pi = Some
28     (Stt (Let x b e) env k)  $\Rightarrow$ 
29   seq_step_up (b, env) (e', env')  $\Rightarrow$ 
30   concur_step
31     (trpl, ys)
32     (trpl(pi @ [LCall x]  $\mapsto$ 
33       (Stt e' env'
34         ((Ctn x e env) # k))), ys) |
35 LetMkCh :
36   leaf trpl pi  $\Rightarrow$ 
37   trpl pi = Some (Stt (Let x MkChn e) env k)  $\Rightarrow$ 
38   concur_step
39     (trpl, ys)
40     (trpl(pi @ [LNxt x]  $\mapsto$ 
41       (Stt e (env(x  $\mapsto$  (VChn (Chn pi x)))) k)), ys) |
42 LetSpwn :
43   leaf trpl pi  $\Rightarrow$ 
44   trpl pi = Some
45     (Stt (Let x (Spwn ec) e) env k)  $\Rightarrow$ 
46   concur_step
47     (trpl, ys)
48     (trpl(
49       pi @ [LNxt x]  $\mapsto$ 
50       (St e (env(x  $\mapsto$  VUnt)) k),
51       pi @ [LSpwn x]  $\mapsto$ 
52       (St ec env []), ys) |
53 LetSync :
54   leaf trpl pis  $\Rightarrow$ 
55   trpl pis = Some
56     (Stt (Let xs (Sync xse) es) envs ks)  $\Rightarrow$ 
57   envs xse = Some
58     (VClsr (SendEvt xsc xm) envse)  $\Rightarrow$ 
59   leaf trpl pir  $\Rightarrow$ 
60   trpl pir = Some
61     (Stt (Let xr (Sync xre) er) envr kr)  $\Rightarrow$ 
62   envr xre = Some
63     (VClsr (RecvEvt xrc) envre)  $\Rightarrow$ 

```

```

64     envse xsc = Some (VChn c) ==>
65     envre xrc = Some (VChn c) ==>
66     envse xm = Some vm ==>
67     concur_step
68       (trpl, ys)
69       (trpl(
70         pis @ [LNxt xs] ↦
71         (Stt es (envs(xs ↦ VUnt)) ks),
72         pir @ [LNxt xr] ↦
73         (Stt er (envr(xr ↦ vm)) kr)),
74         ys ∪ {(pis, c, pir)})
75
76
1   inductive star : : ('a ⇒ 'a ⇒ bool) ⇒ 'a ⇒ 'a ⇒ bool
2   for r where
3     refl : star r x x |
4     step : r x y ==> star r y z ==> star r x z
5

```

4 Dynamic Communication

```

1   inductive is_send_path : :
2     trace_pool ⇒ chan ⇒
3     control_path ⇒ bool where
4     intro :
5       trpl piy = Some
6         (Stt (Let xy (Sync xe) en) env k) ==>
7       env xe = Some
8         (VClsr (SendEvt xsc xm) enve) ==>
9       enve xsc = Some (VChn c) ==>
10      is_send_path trpl c piy
11
12  inductive is_recv_path : :
13    trace_pool ⇒ chan ⇒
14    control_path ⇒ bool where
15    intro :
16      trpl piy = Some
17        (Stt (Let xy (Sync xe) en) env k) ==>
18      env xe = Some
19        (VClsr (RecvEvt xrc) enve) ==>
20      enve xrc = Some (VChn c) ==>
21      is_recv_path trpl c piy
22
23
1
2   inductive every_two : :
3     ('a ⇒ bool) ⇒

```

```

4      ('a  $\Rightarrow$  'a  $\Rightarrow$  bool)  $\Rightarrow$ 
5      bool where
6      intro : ( $\forall$  pi1 pi2 .
7          p x1  $\rightarrow$ 
8          p x2  $\rightarrow$ 
9          r x1 x2)  $\Rightarrow$ 
10         every_two p r
11
12     inductive ordered : : 'a list  $\Rightarrow$  'a list  $\Rightarrow$  bool where
13         left : prefix pi1 pi2  $\Rightarrow$  ordered pi1 pi2 |
14         right : prefix pi2 pi1  $\Rightarrow$  ordered pi1 pi2
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```

```

1
2     inductive one_shot : : trace_pool  $\Rightarrow$  chan  $\Rightarrow$  bool where
3         intro :
4             every_two
5                 (is_send_path trpl c) op=  $\Rightarrow$ 
6                 one_shot trpl c
7
8     inductive fan_out : : trace_pool  $\Rightarrow$  chan  $\Rightarrow$  bool where
9         intro :
10             every_two
11                 (is_send_path trpl c) ordered  $\Rightarrow$ 
12                 fan_out trpl c
13
14     inductive fan_in : : trace_pool  $\Rightarrow$  chan  $\Rightarrow$  bool where
15         intro :
16             every_two
17                 (is_recv_path trpl c) ordered  $\Rightarrow$ 
18                 fan_in trpl c
19
20     inductive one_to_one : : trace_pool  $\Rightarrow$  chan  $\Rightarrow$  bool where
21         intro :
22             fan_out trpl c  $\Rightarrow$ 
23             fan_in trpl c  $\Rightarrow$ 
24             one_to_one trpl c
25
26

```

5 Static Semantics

```

1
2     datatype abstract_value =
3         AChn var |
4         AUnt |
5         APrim prim
6

```

```

7  type_synonym abstract_env = var  $\Rightarrow$  abstract_value set
8
9  fun rslt_var : : exp  $\Rightarrow$  var where
10   rslt_var (Rslt x) = x |
11   rslt_var (Let _ _ e) = (rslt_var e)
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```

```

1
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3  inductive may_be_eval_exp : :
4    abstract_env * abstract_env  $\Rightarrow$ 
5    exp  $\Rightarrow$  bool where
6    Result :
7      may_be_eval_exp (V, C) (RESULT x) |
8    let_Unt :
9      {AUnt}  $\subseteq$  V x  $\Rightarrow$ 
10      may_be_eval_exp (V, C) e  $\Rightarrow$ 
11      may_be_eval_exp (V, C) (Let x Unt e) |
12    let_Chan :
13      {AChn x}  $\subseteq$  V x  $\Rightarrow$ 
14      may_be_eval_exp (V, C) e  $\Rightarrow$ 
15      may_be_eval_exp (V, C) (Let x (MkChn) e) |
16    let_SendEvt :
17      {APrim (SendEvt xc xm)}  $\subseteq$  V x  $\Rightarrow$ 
18      may_be_eval_exp (V, C) e  $\Rightarrow$ 
19      may_be_eval_exp (V, C) (Let x (Prim (SendEvt xc xm)) e
20    ) |
21    let_RecvEvt :
22      {APrim (RecvEvt xc)}  $\subseteq$  V x  $\Rightarrow$ 
23      may_be_eval_exp (V, C) e  $\Rightarrow$ 
24      may_be_eval_exp (V, C) (Let x (Prim (RecvEvt xc)) e) |
25    let_Pair :
26      {APrim (Pair x1 x2)}  $\subseteq$  V x  $\Rightarrow$ 
27      may_be_eval_exp (V, C) e  $\Rightarrow$ 
28      may_be_eval_exp (V, C) (Let x (Pair x1 x2) e) |
29    let_Left :
30      {APrim (Left xp)}  $\subseteq$  V x  $\Rightarrow$ 
31      may_be_eval_exp (V, C) e  $\Rightarrow$ 
32      may_be_eval_exp (V, C) (Let x (Left xp) e) |
33    let_Right :
34      {APrim (Right xp)}  $\subseteq$  V x  $\Rightarrow$ 
35      may_be_eval_exp (V, C) e  $\Rightarrow$ 
36      may_be_eval_exp (V, C) (Let x (Right xp) e) |
37    let_Abs :
38      {APrim (Abs f' x' e')}  $\subseteq$  V f'  $\Rightarrow$ 
39      may_be_eval_exp (V, C) e'  $\Rightarrow$ 
40      {APrim (Abs f' x' e')}  $\subseteq$  V x  $\Rightarrow$ 
41      may_be_eval_exp (V, C) e  $\Rightarrow$ 
42      may_be_eval_exp (V, C) (Let x (Abs f' x' e') e) |

```



```

42 let_Spawn :
43   {AUnt}  $\subseteq V$  x  $\implies$ 
44   may_be_eval_exp (V, C) ec  $\implies$ 
45   may_be_eval_exp (V, C) e  $\implies$ 
46   may_be_eval_exp (V, C) (Let x (Spwn ec) e) |
47 let_Sync :
48    $\forall$  xsc xm xc .
49   (APrim (SendEvt xsc xm))  $\in V$  xe  $\longrightarrow$ 
50   AChn xc  $\in V$  xsc  $\longrightarrow$ 
51   {AUnt}  $\subseteq V$  x  $\wedge V$  xm  $\subseteq C$  xc  $\implies$ 
52    $\forall$  xrc xc .
53   (APrim (RecvEvt xrc))  $\in V$  xe  $\longrightarrow$ 
54   AChn xc  $\in V$  xrc  $\longrightarrow$ 
55   C xc  $\subseteq V$  x  $\implies$ 
56   may_be_eval_exp (V, C) e  $\implies$ 
57   may_be_eval_exp (V, C) (Let x (Syync xe) e) |
58 let_Fst :
59    $\forall$  x1 x2.
60   (APrim (Pair x1 x2))  $\in V$  xp  $\longrightarrow$ 
61   V x1  $\subseteq V$  x  $\implies$ 
62   may_be_eval_exp (V, C) e  $\implies$ 
63   may_be_eval_exp (V, C) (Let x (Fst xp) e) |
64 let_Snd :
65    $\forall$  x1 x2 .
66   (APrim (Pair x1 x2))  $\in V$  xp  $\longrightarrow$ 
67   V x2  $\subseteq V$  x  $\implies$ 
68   may_be_eval_exp (V, C) e  $\implies$ 
69   may_be_eval_exp (V, C) (Let x (Snd xp) e) |
70 let_Case :
71    $\forall$  x1' .
72   (APrim (Left x1'))  $\in V$  xs  $\longrightarrow$ 
73   V x1'  $\subseteq V$  x1  $\wedge V$  (rslt_var e1)  $\subseteq V$  x  $\wedge$ 
74   may_be_eval_exp (V, C) e1  $\implies$ 
75    $\forall$  xr' .
76   (APrim (Right xr'))  $\in V$  xs  $\longrightarrow$ 
77   V xr'  $\subseteq V$  xr  $\wedge V$  (rslt_var er)  $\subseteq V$  x  $\wedge$ 
78   may_be_eval_exp (V, C) er  $\implies$ 
79   may_be_eval_exp (V, C) e  $\implies$ 
80   may_be_eval_exp (V, C) (Let x (Case xs x1 e1 xr er) e)
81 |
82 let_App :
83    $\forall$  f' x' e' .
84   (APrim (Abs f' x' e'))  $\in V$  f  $\longrightarrow$ 
85   V xa  $\subseteq V$  x'  $\wedge$ 
86   V (rslt_var e')  $\subseteq V$  x  $\implies$ 
87   may_be_eval_exp (V, C) e  $\implies$ 
88   may_be_eval_exp (V, C) (Let x (App f xa) e)
89

```

```

1
2
3 fun abstract : : val  $\Rightarrow$  abstract_value where
4   abstract VUnt = AUnt |
5   abstract VChn (Chn pi x) = AChn x |
6   abstract VClsr p env = APrim p
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```

```

1
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3
4 inductive
5   may_be_eval_val : :
6   abstract_env * abstract_env  $\Rightarrow$  val  $\Rightarrow$  bool and
7   may_be_eval_env : :
8   abstract_env * abstract_env  $\Rightarrow$  val_env  $\Rightarrow$  bool where
9   Unt :
10     may_be_eval_val (V, C) VUnt |
11   Chan :
12     may_be_eval_val (V, C) VChn c |
13   SendEvt :
14     may_be_eval_env (V, C) env  $\Rightarrow$ 
15     may_be_eval_val (V, C) (VClsr (SendEvt _ _) env) |
16   RecvEvt :
17     may_be_eval_env (V, C) env  $\Rightarrow$ 
18     may_be_eval_val (V, C) (VClsr (RecvEvt _) env) |
19   Left :
20     may_be_eval_env (V, C) env  $\Rightarrow$ 
21     may_be_eval_val (V, C) (VClsr (Left _) env) |
22   Right :
23     may_be_eval_env (V, C) env  $\Rightarrow$ 
24     may_be_eval_val (V, C) (VClsr (Right _) env) |
25   Abs :
26     {(APrim (Abs f x e))}  $\subseteq$  V f  $\Rightarrow$ 
27     may_be_eval_exp (V, C) e  $\Rightarrow$ 
28     may_be_eval_env (V, C) env  $\Rightarrow$ 
29     may_be_eval_val (V, C) (VClsr (Abs f x e) env) |
30   Pair :
31     may_be_eval_env (V, C) env  $\Rightarrow$ 
32     may_be_eval_val (V, C) (VClsr (Pair _ _) env) |
33   intro :
34      $\forall$  x v .
35     env x = Some v  $\longrightarrow$ 
36     {abstract v}  $\subseteq$  V x  $\wedge$  may_be_eval_val (V, C) v  $\Rightarrow$ 
37     may_be_eval_env (V, C) env
38
39

```

1

```

2   inductive may_be_eval_stack : :
3     abstract_env * abstract_env =>
4     abstract_value set => cont list => bool where
5     Empty :
6       may_be_eval_stack (V, C) valset [] |
7     Nonempty :
8       valset ⊆ V x =>
9       may_be_eval_exp (V, C) e =>
10      may_be_eval_env (V, C) env =>
11      may_be_eval_stack (V, C) (V (rslt_var e)) k =>
12      may_be_eval_stack (V, C) valset ((Ctn x e env) # k)
13
14
15  inductive may_be_eval_state : :
16    abstract_env * abstract_env =>
17    state => bool where
18    intro :
19      may_be_eval_exp (V, C) e =>
20      may_be_eval_env (V, C) env =>
21      may_be_eval_stack (V, C) (V (rslt_var e)) k =>
22      may_be_eval_state (V, C) (Stt e env k)
23
24  inductive may_be_eval_pool : :
25    abstract_env * abstract_env =>
26    trace_pool => bool where
27    intro :
28      ∀ pi st .
29      trpl pi = Some st →
30      may_be_eval_state (V, C) st =>
31      may_be_eval_pool (V, C) trpl
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1
2   theorem may_be_eval_preserved_under_concur_step : "
3     may_be_eval_pool (V, C) trpl =>
4     concur_step (trpl, ys) (trpl', ys') =>
5     may_be_stati_eval_pool (V, C) trpl'"
6 proof outline
7 qed
8
9   theorem may_be_eval_preserved_under_concur_step_star : "
10    may_be_eval_pool (V, C) trpl =>
11    star concur_step (trpl, ys) (trpl', ys') =>
12    may_be_concur_step (V, C) trpl'"
13 proof outline
14 qed
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```

2  theorem trace_pool_snapshot_value_not_bound_sound : "
3    env x = Some v  $\implies$ 
4    trpl pi = Some (Stt e env k)  $\implies$ 
5    may_be_eval_pool (V, C) trpl  $\implies$ 
6    {abstract v}  $\subseteq$  V x "
7  proof outline
8  qed
9
1
2  theorem trace_pool_always_value_not_bound_sound : "
3    env' x = Some v  $\implies$ 
4    may_be_eval_pool (V, C) trpl  $\implies$ 
5    star concur_step (trpl, ys) (trpl', ys')  $\implies$ 
6    trpl' pi = Some (Stt e' env' k')  $\implies$ 
7    {abstract v}  $\subseteq$  V x"
8  proof outline
9  qed
10
11 theorem exp_always_value_not_bound_sound : "
12   env' x = Some v  $\implies$ 
13   may_be_eval_exp (V, C) e  $\implies$ 
14   star concur_step
15     ([[]  $\mapsto$  (Stt e ( $\lambda$  _ . None) [])], ys)
16     (trpl', ys')  $\implies$ 
17   trpl' pi = Some (Stt e' env' k')  $\implies$ 
18   {abstract v}  $\subseteq$  V x"
19 proof outline
20 qed
21
22
1  inductive is_super_exp : : exp  $\Rightarrow$  exp  $\Rightarrow$  bool  where
2    Refl :
3      is_super_exp e e |
4      let_Spawn_Child
5        is_super_exp ec e  $\implies$ 
6        is_super_exp (Let x (Spwn ec) en) e |
7      let_Case_Left :
8        is_super_exp el e  $\implies$ 
9        is_super_exp (Let x (case xs xl el xr er) en) e |
10     let_Case_Right :
11       is_super_exp er e  $\implies$ 
12       is_super_exp (Let x (case xs xl el xr er) en) e |
13     let_Abs_Body : "
14       is_super_exp eb e  $\implies$ 
15       is_super_exp (Let x (Abs f xp eb) en) e |
16     Let :
17       is_super_exp en e  $\implies$ 
18       is_super_exp (Let x b en) e

```

```

19
20 inductive is_super_exp_left : : exp  $\Rightarrow$  exp  $\Rightarrow$  bool where
21   Refl :
22     is_super_exp_left e0 e0 |
23   let_Spawn_Child :
24     is_super_exp_left e0 (Let x (Spwn ec) en)  $\Rightarrow$ 
25     is_super_exp_left e0 ec |
26   let_Case_Left :
27     is_super_exp_left e0 (Let x (case xs xl e1 xr er) en)
 $\Rightarrow$ 
28     is_super_exp_left e0 e1 |
29   let_Case_Right : "
30     is_super_exp_left e0 (Let x (case xs xl e1 xr er) en)
 $\Rightarrow$ 
31     is_super_exp_left e0 er |
32   let_Abs_Body :
33     is_super_exp_left e0 (Let x (Abs f xp eb) en)  $\Rightarrow$ 
34     is_super_exp_left e0 eb |
35   Let :
36     is_super_exp_left e0 (Let x b en)  $\Rightarrow$ 
37     is_super_exp_left e0 en
38
39 inductive is_super_exp_over_prim : : exp  $\Rightarrow$  prim  $\Rightarrow$  bool
   where
40   SendEvt :
41     is_super_exp_over_prim e0 (SendEvt xC xM) |
42   RecvEvt :
43     is_super_exp_over_prim e0 (RecvEvt xC) |
44   Pair :
45     is_super_exp_over_prim e0 (Pair x1 x2) |
46   Left :
47     is_super_exp_over_prim e0 (Left x) |
48   Right : "
49     is_super_exp_over_prim e0 (Right x) |
50   Abs :
51     is_super_exp_left e0 eb  $\Rightarrow$ 
52     is_super_exp_over_prim e0 (Abs fp xp eb)
53
54 inductive
55   is_super_exp_over_env : : exp  $\Rightarrow$  env  $\Rightarrow$  bool and
56   is_super_exp_over_val : : exp  $\Rightarrow$  val  $\Rightarrow$  bool where
57   VUnt :
58     is_super_exp_over_val e0 VUnt |
59   VChn :
60     is_super_exp_over_val e0 (VChn c) |
61   VClsr : "
62     is_super_exp_over_prim e0 p  $\Rightarrow$ 
63     is_super_exp_over_env e0 env'  $\Rightarrow$ 
64     is_super_exp_over_val e0 (VClsr p env') |
65   intro : "

```

```

66      $\forall x v .$ 
67     env x = Some v  $\longrightarrow$ 
68     is_super_exp_over_val e0 v  $\implies$ 
69     is_super_exp_over_env e0 env
70
71 inductive is_super_exp_over_stack : : exp  $\Rightarrow$  cont list  $\Rightarrow$ 
72   bool where
73   Empty :
74     is_super_exp_over_stack e0 [] |
75   Nonempty :
76     is_super_exp_left e0 ek  $\implies$ 
77     is_super_exp_over_env e0 envk  $\implies$ 
78     is_super_exp_over_stack e0 k  $\implies$ 
79     is_super_exp_over_stack e0 ((Ctn xk ek envk) # k)
80
81 inductive is_super_exp_over_state : : exp  $\Rightarrow$  state  $\Rightarrow$  bool
82   where
83   intro :
84     is_super_exp_left e0 e  $\implies$ 
85     is_super_exp_over_env e0 env  $\implies$ 
86     is_super_exp_over_stack e0 k  $\implies$ 
87     is_super_exp_over_state e0 (Ctn e env k)
88
89
90 lemma is_super_exp_trans : "
91   is_super_exp ez ey  $\implies$ 
92   is_super_exp ey ex  $\implies$ 
93   is_super_exp ez ex"
94 proof outline
95 qed
96
97
98 lemma is_super_exp_over_state_preserved : "
99   concur_step (trpl, ys) (trpl', ys')  $\implies$ 
100    $\forall pi st.$ 
101   trpl pi = Some st  $\longrightarrow$ 
102   is_super_exp_over_state e0 st  $\implies$ 
103   trpl' pi' = Some st'  $\implies$ 
104   is_super_exp_over_state e0 st'"
105 proof outline
106 qed
107
108
109 lemma state_always_exp_not_reachable_sound : "
110   star concur_step (trpl0, ys0) (trpl', ys')  $\implies$ 
111   trpl0 = [[]  $\mapsto$  (Stt e0 ( $\lambda \_ . None$ ) [])]  $\implies$ 
112   trpl' pi' = Some st'  $\implies$ 
113   is_super_exp_over_state e0 st' "

```

```

7   proof outline
8   qed
9
10  lemma exp_always_exp_not_reachable_sound : "
11    star concur_step
12    ([[  $\mapsto$  (Stt e0 ( $\lambda$  _ . None) [])], {}))
13    (trpl', H')  $\impl$ 
14    trpl' pi' = Some (Stt e' env' k'))  $\impl$ 
15    is_super_exp e0 e' "
16  proof outline
17  qed
18
19

```