Introduction to SESF (Services and Systems Framework)

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Outline

Program structure

- Program
  - header: program name + program parameters
  - main code + functions + input functions
  - assumptions of inputs, atomicity, progress // for analysis only
- `startSystem(`*`pname`*`(`*`params`*`))`: instantiates program
  - basic system is created with a unique system id (abbr sid)
  - instantiating thread executes main and returns
  - system remains
- Special *read-only* variables available for code
  - `mysid`: sid of this system
  - `mytid`: tid of this thread
- *All* parameters are read-only

Input functions

- Input function:
  - *retType* `mysid.`*fname*`(`*params*`) {`*body*`}`
  - retType can be `void` or absent (for arbitrary type)
- Thread in environment can call input functions of system
  - syntax: *sid*`.`*fname*`(`*params*`)`
  - thread enters system, executes function, returns
- Above is the only way for systems to interact
  (other than instantiating a program)

Thread creation

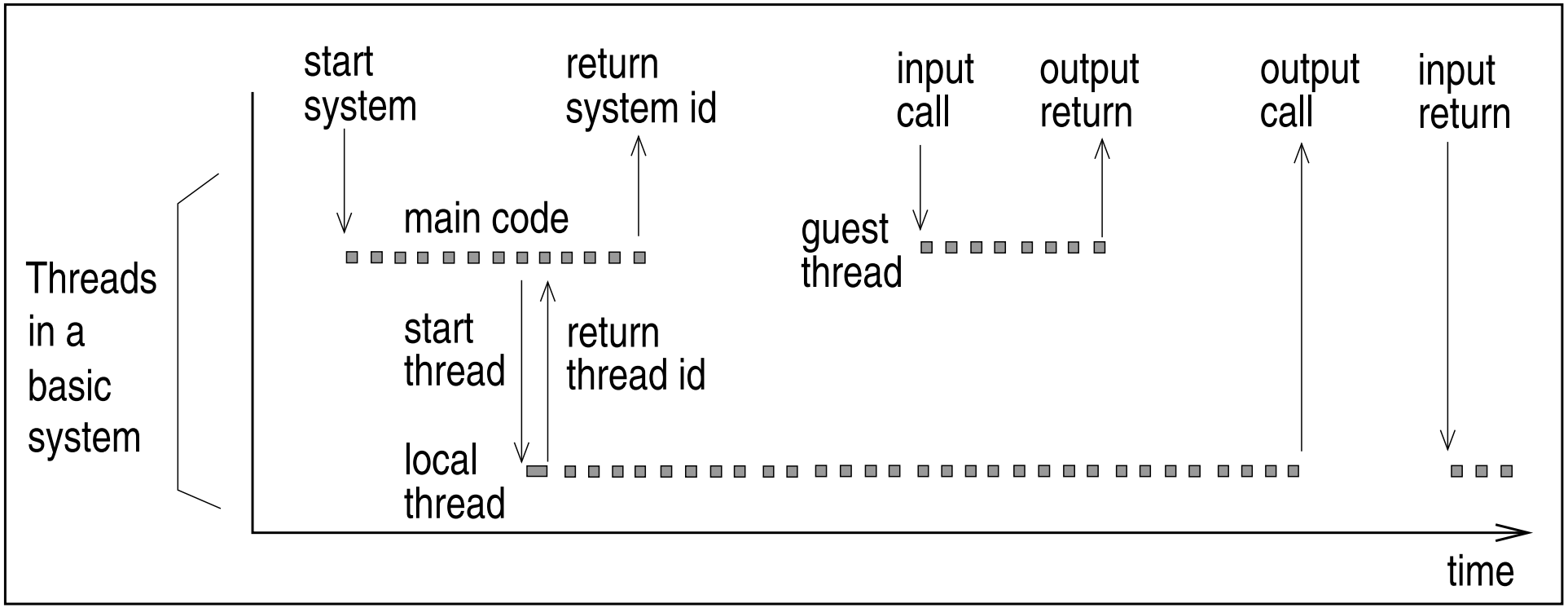
- Can create a thread executing a *local non-input* function
  - `startThread(`*`func`*`(`*`params`*`))`
  - returns a unique thread id (abbr tid)
  - thread ends when it reaches end of `func()`
- local threads: those created in the system
- guest threads: those that came from the environment

System termination

- Platform eventually terminates a system if
  - a thread in system has executed `endSystem()`
  - system is continuously in a *endable* state
- System is endable
  - no guest threads in the system
  - no local thread of the system is in another system

  Ensures that a thread is not left in limbo.
- At termination, platform
  - terminates all local threads
  - cleans up system's state

Example: Evolution of Threads in a Basic System



Assumptions of a Program

- Analyzing a program requires three kinds of assumptions
  - input assumptions: about inputs from systems in environment
  - atomicity assumption: atomicity expected from platform
  - progress assumption: progress expected from platform
- All are defined (explicitly or by default) in the program
- They are only for analysis; program need not check them

Input assumptions

- Placed at input function headers and output call returns
  - syntax: `ia{`*predicate*`}` // predicate in variables and input
  - default: `ia{true}`
- Implicitly includes type constraints on call params and return vals

```
program xyz(int p) {
  ia{p prime}
  int x;
  ...
  function mysid.fn1(int q) {
     ia{x + p > q}
     int y;
     ...
     ret ← sid.fn2(.);
     ia{predicate in p,x,q,y,ret}
     ...
  }
}
```

Atomicity assumption

- An execution α of a code chunk is atomic means that while α is ongoing, no (other) thread can influence or observe α
  - thus α appears to be indivisble or "instantaneous"
- Code chunk S is atomic if every execution of S is atomic
- Every platform provides some atomicity
  - bare hardware: read word, write word, test-and-set, ...
  - OS: above + locks, condition variables, semaphores, ...
- Atomicity assumption of a program identifies the atomicity assumed to be provided by the platform
- Without them, (multi-threaded) program is not well-defined

Effective Atomicity

- Not all of a program need be covered by the atomicity assumption
- Program can ensure that an execution α of a code chunk is atomic by ensuring that there is no simultaneous conflicting execution β
  - α and β conflict if one writes to memory accessed by the other
- Program does this by isolating conflicting code
  - in time, e.g., by thread synchronization
  - in memory, e.g., by duplicating data
- Effective atomicity can depend on program's input assumptions
  - e.g., at most one ongoing call of a non-reentrant function

Progress assumption

- For a program to satisfy progress properties, the platform must execute its threads with some progress.
- Two kinds of minimal progress: weak fairness and strong fairness
- Weak fairness for a thread
  - thread regularly gets processor cycles, i.e., non-zero speed

  Ensures that it gets past a continuously-unblocked instruction
- Strong fairness for a blocking instruction S
  - any thread at S eventually gets past if S is repeatedly (but not necessarily continuously) unblocked
- Progress assumption states the fairness expected of the platform

Aggregate Systems and Composite Systems

- For a basic system x, the aggregate system x is x and all basic systems created directly or indirectly by x
- For a program Y, the aggregate system Y is the aggregate system of Y's instantiation without renaming or constraining its params.
- The evolutions and properties of program Y are those of aggregate system Y
- Aggregate system inputs: union of component systems' inputs, except for inputs explicitly hidden from environment
- Aggregate system outputs: union of component systems' outputs that are directed to the environment of the aggregate system.
- Composite system: an arbitrary collection of basic systems
  - inputs, outputs: same as in aggregate system

Outline

ProdCons

```
program ProdCons(J) {                    // J: max # of items produced
  ia {J ≥ 1}                                        // input assumption
  lck ← startSystem(Lock());
  cons ← startSystem(Cons(lck, J));
  prod ← startSystem(Prod(lck, cons, J));
  return [prod, cons];                                    // end main

  atomicity assumption { }          // none; single-threaded
  progress assumption {weak fairness}
}
```

- ProdCons may be a "make" program
- ProdCons may be a "virtual" program,
  e.g., humans at three computers, synchronizing over phone

Lock

```
program Lock() {
  ia {...}
  ...
  return mysid;

  input void mysid.acq()
     ia {...}
     return;

   input void mysid.rel()
     ia {...}
     return;

   input void mysid.end()
     ia {...}
     endSystem();
     return;

  atomicity assumption {
     word read, word write
  }

  progress assumption {
     weak fairness of threads
  }
}
```

Producer and Consumer


```
program Producer(lck,cons,J) {
  ia {...}
  t ← startThread(produce());
  return mysid;

  function void produce()
    for (i in 1..J)
       produce item;
       lck.acq();
       cons.put(item);
       lck.rel();
    endSystem();

   atomicity & progress
     assumptions
}
```

```
program Consumer(lck, J) {
  ia {...}
  t ← startThread(consume());
  return mysid;

  function void consume()
    for (i in 1..J) {
       lck.acq();
       consume item;
       lck.rel();
    lck.end();
    endSystem();

  input void mysid.put(item)
    ia {...}
    return;

  atomicity & progress assumps
}
```

Outline

Service program structure

- A service program is essentially a state machine organized into "input" and "output" functions

```
service prog name(params) {
  ic {predicate in params}
  <main>                          // define and initialize variables
  <input functions>
  <output functions>
  <atomicity and progress assumptions>
}
```

- Does not create any other system
  - so only one basic system, even for a distributed service
- Creates threads only to execute output functions (if any)
- Maximal atomicity: every atomic step does input or output

Outline

Input function

- Consists of
  - input part: executed atomically when function is called
  - output part: executed atomically when function returns
- Input part consists of
  - input condition: predicate in vars and params, no side-effect
  - body: non-blocking deterministic update to main's vars

  Body is executed if input condition holds, o/w fault
- Output part consists of
  - output condition and body, as in input part

  Body is executed only if output condition holds, o/w block
- Note: input function never calls the environment

Example: Bounded Counter – 1


```
service Cntr1(N) {
    ic {N in 0..100}
    int x ← 0;
    return mysid;

    input mysid.add(int d) {
        ic {d in -2..2}
        oc {x+d in 0..N}
        x ← x + d;
        return;
    }
}
```

- Allows multiple add calls ongoing simultaneously

Possible evolution

- *u* does
  `s ← startSystem(Cntr(3))`
- *u* calls `s.add(2)`
- *u* returns
- *v* calls `s.add(2)` `// blocks`
- *w* calls `s.add(-1)`
- *w* returns
- *v* returns

Example: Bounded Counter – 2


```
service Cntr2(N) {
  ...
  input mysid.add(int d) {
    ic {d in -2..2}
    output(rval) {
      oc {(x+d in 0..N)
          and (rval in x..x+d)}
      x ← x + d;
      return rval;
} } }
```

Like Cntr1 except add() returns a value between old x and new x

- Note that rval is set not in body but in output condition
- add() has external non-determinism
  - external: choice is immediately visible to environment

Example: Bounded Counter – 3

- service Cntr3(N) {

```
  ...
  input mysid.add(int d) {
    ic {d in -2..2}
    output(δ) {
       oc {(x+δ in 0..N) and
            ((d<0 and δ in d..0) or
             (d≥0 and δ in 0..d))
       }
       x ← x + δ;
       return;
  } } }
```

Like Cntr1 except add(d) updates x by some value between d and 0

- add() has internal non-determinism
  - internal: choice is not immediately visible to environment

Input function: general case


```
input retType sid.fname(param)
  ic {predicate}
  body
```

input part

```
  output(rval, internalParam)
    oc {pred}
    body
    return rval;
```

output part

- output(.): introduces additional parameters for output part
  - *rval*: return value; allows external nondeterminism
  - *internalParam*: allows internal nondeterminism
  - parameters can have any value allowed by the output condition
  - parameters not updated in output body
- The *sid* field in the header can differ from mysid (Why?)

Outline

Output function

- Output function: "reverse" of an input function
- Consists of an output part followed by an input part
- Output part: output condition and body
  - body ends in call to environment, say *sid.fn*(*param*)
  - atomically create thread and execute body (including call) only if output condition holds, o/w block
- Input part: input condition and body
  - body starts with the call's return value (if any)
  - when call returns, atomically execute body and terminate thread if input condition holds, o/w fault
- Never called by environment.
- Program has no other call to *sid.fn*(.)
  - so all its *sid.fn*(.) calls are caputed by the output condition

Output function: general case

- output *fname*(*extParam*, *intParam*) {
  oc {*oc predicate*}
  output body
  rval ← *sid.fn*(*args*);
  ic {*ic predicate*}
  input body
  }

output part,
ends at *sid.fn(.)*

input part,
begins at *rval*

- *extParam*: *sid* and *args* of the call
- *intParam*: parameters to achieve internal nondeterminism

Example: Tick Generator – 1


```
service Tkr1(Sid s, int K) {
  ic {K > 0}
  int ongoing ← 0;
  return;

  output doTick(int n) {
    oc {ongoing < K and n > 0}
    ongoing++;
    s.tick(n);
    ic {true}
    ongoing--;
  }
}
```

- Issues `s.tick(n)` calls, where `n` is positive int
- At most `K` calls ongoing at any time

Example: Tick Generator – 2


```
service Tkr2(Sid s, int K) {
  ic {K > 0}
  int ongoing ← 0;
  bool active ← true;
  return;

  output doTick(int n) {
    oc {active and
        ongoing < K and n > 0}
    ongoing++;
    bool rval ← s.tick(n);
    ic {true}
    if (not rval)
       active ← false;
    ongoing--;
  }
}
```

- Like Tkr1 except
  - tick() returns a boolean
  - false return stops the service

Example: Tick Generator – 3


```
service Tkr3(Sid s, int K) {
  ic {K > 0}
  int ongoing ← 0;
  bool lowMode ← false;
  return;

  out-
put doTick(int n, bool chm) {
    oc {(lowMode and n = 1) or
        (not lowMode and n > 0)}
    ongoing++;
    if (chm) lowMode ← true;
    s.tick(n);
    ic {true}
    ongoing--;
  }
}
```

- Like Tkr1 except
  - has a "low" mode: tick(1) calls only
  - entry to low mode is internally nondeterministic

Outline

Atomicity assumption

- Every service program has the same atomicity assumption
  - every input part is atomic
  - every output part is atomic
- Main is is also atomic, but comes for free because
  - it is executed by one thread
  - it does not interact with the environment before the return

Progress assumption

- Predicate whose terms are restricted to be leads-to assertions
  - `(A` *leads-to* `B)` $\Rightarrow$ `(C` *leads-to* `D)`
  - `forsome(j: (A(j)` *leads-to* `B(j)))`
    $\Rightarrow$ `forall(k: (C(k)` *leads-to* `D(k)))`
- Avoid fairness assertions because
  - clumsier to prove (and invert)
  - often inconvenient (e.g., message-passing service)
- Progress assumption must be locally realizable, i.e., realizable without requiring inputs from the environment.
  - "*u* holds lock" *leads-to* "*u* calls `rel()`" // not ok
  - "*u* calls `acq()`" *leads-to* "*u* returns from call" // not ok

Outline

Lock Service – 1

```
service LockService() {
 ic {true}
 ...
 ending ← false;
 return mysid;

 input void mysid.acq()
   ic {not ending and
       mytid does not have lock}
   ...
   oc {no user has lock}
   ...
   return;

 input void mysid.rel()
   ic {not ending and
       mytid has lock}
   ...
   oc {true}
   return;
```

```
 input void mysid.end()
   ic {not ending}
   ending ← true;
   oc {true}
   return;
}
```

```
atomicity assumption {input parts and output parts}

progress assumption {                    // u, v range over tids

  forall(u: (u in rel)  leads-to  (not u in rel));

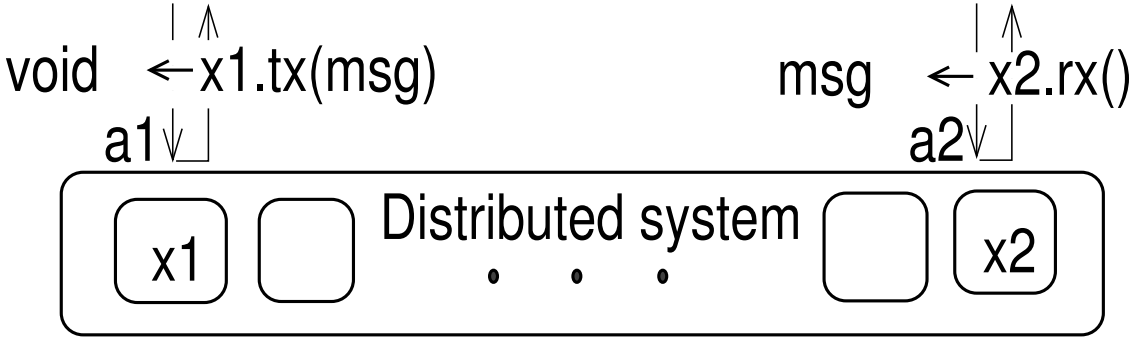
  forall(u: (u holds lock)  leads-to  (u in rel))
   ⇒ forall(u: (u in acq)  leads-to  (not u in acq));

  forall(u: (u in end)  leads-to  (not u in end));
 }
}
```

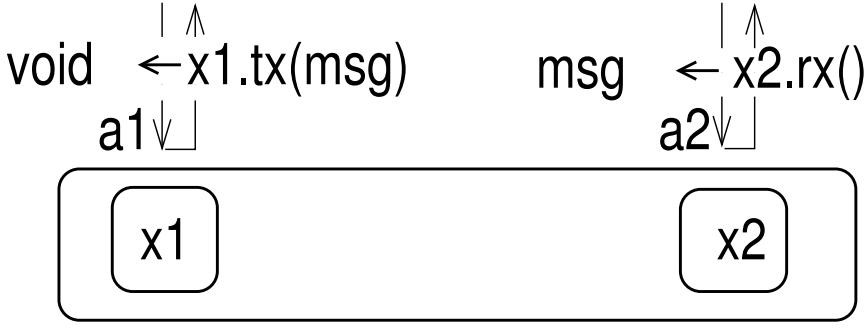
Outline

Distributed services options

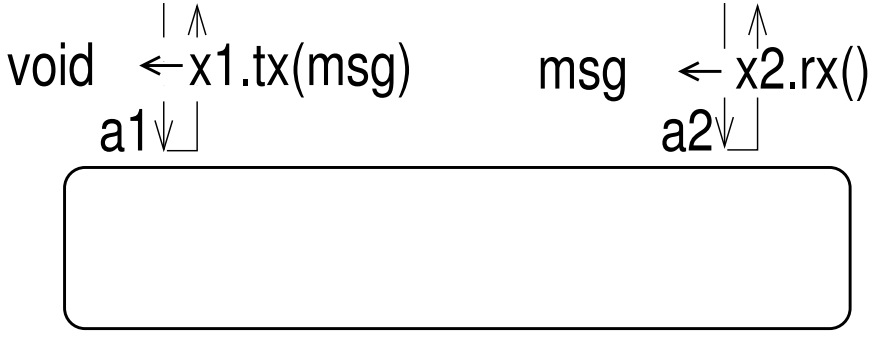
Distributed message-passing system



Msg-passing service (option 1)



Msg-passing service (option 2)



Msg-passing service program (option 2)


```
service MsgService(a1, a2) {
    ic {...}
    ...                 // define variables
    x1 ← sid();         // sid of sender at a1
    x2 ← sid();         // sid of receiver at a2
    return [x1,x2];

    input void x1.tx(msg)
        ic {...} ...
        oc {...} ...
        return;

    input Msg x2.rx()
        ic {...} ...
        output(msg) {
          oc {...} ...
          return msg;

    atomicity assumption {...}
    progress assumption {...}
}
```

Outline

A implements B – 1

- General programs A and B // B need not be service
- A implements B if, roughly speaking,
  - A can accept every input that B can accept
  - any output of A is an output that B can do
  - A satisfies B's progress assumption
- To formalize, define following for any evolution x
  - $ext(x)$: the io sequence of x
  - x is safe wrt B if x is fault-free and $ext(x)$ is generated by a fault-free evolution of B.
  - x is complete wrt B if x is fault-free and $ext(x)$ is generated by a fault-free evolution of B that satisfies B's progress assumption

A implements B – 2

- Definition: A implements B if
  - Safety:
    for every finite evolution x of A s.t. x safe wrt B
    - for every input e of B, if $x \circ \langle e \rangle$ is safe wrt B then input e at x does not make A faulty
    - any step that A can do at the end of x is fault-free, and if that step outputs f then $x \circ \langle f \rangle$ is safe wrt B
  - Progress:
    - if evolution x of A is safe wrt B and satisfies A's progress assumption, then x is complete wrt B
- Achieves compositionality: i.e., C is preserved by $C[B/A]$
- But it's not in terms of programs A and B

Program-version: *A implements B* – 1

- Program A, service B
- Construct a program $\overline{B} = B[\text{inputs} \leftrightarrow \text{outputs}]$
  - $\overline{B}$: can output e whenever B can input e, and vice versa
  - $\overline{B}$: most general environment for any implementation of B
  - referred to as inverse of B
- Obtaining $\overline{B}$ is easy for a service program
  - treat $B.main$'s return value as a parameter of B-inverse
  - change every B input function $\longrightarrow$ $\overline{B}$ output function
    - input part $\longrightarrow$ output part
    - output part $\longrightarrow$ input part
  - similarly change every B output function $\longrightarrow$ $\overline{B}$ input function
  - B's progress assumption becomes $\overline{B}$'s progress condition

Program version: *A implements B* – 2

- Define program Z that executes A and $\overline{B}$ concurrently

```
program Z() {
  ia {B.ic}
  inputs(); outputs();                    // aggregate Z is closed
  rval ← startSystem( A(param));
  si ← startSystem( B̄(param, rval));
  return mysid;

  atomicity assumption {}
  progress assumption {weak fairness}
}
```

- A implements B if program Z satisfies
  - for every input condition ic{P} in $\overline{B}$:
    Inv ((thread at si.ic{P}) $\Rightarrow$ si.P) (safety condition)
  - si.(progress condition) (progress condition)

Outline

```
~~service LockService() {~~
program LockServiceInverse(lck) {  // lck: lock system
  ic {true}
  ...
  ending ← false;
  return mysid;

  output doAcq() ~~input void mysid.acq()~~
     ~~ic~~ oc {not ending and
             mytid does not have lock}
     ...
     lck.acq();                        // add call
     ~~oc~~ ic {no user has lock}
     ...
     return;
```

Inverse of Lock Service – 2

```
output doRel() ~~input void mysid.rel()~~
    ~~ic~~ oc {not ending and mytid has lock}
    ...
    lck.rel();                          // add call
    ~~oc~~ ic {true}
    return;

output doEnd() ~~input void mysid.end()~~
    ~~ic~~ oc {not ending}
    ending ← true;
    lck.end();                          // add call
    ic {true}
    return;

atomicity assumption {...}                  // as before
progress ~~assumption~~ condition {....} // as before
```

Program Z for Lock and LockService

- program Z() {
  ia {LockService.ic}
  inputs(); outputs();
  lck ← startSystem(Lock());
  lsi ← startSystem(LockServiceInverse(lck));
  return mysid;

  atomicity assumption {}
  progress assumption {weak fairness}
  }

- Lock() implements LockService() if program Z satisfies
  - Inv(thread t at lsi.doAcq().ic) ⇒ lsi.(no user has lock)
  - lsi.(progress condition)

Outline

Inverse of Msg-passing Service

- ~~service MsgService(a1, a2) {~~
  program MsgServiceInverse(a1, a2, [x1,x2]) {
    ic {...}
    ...
    ~~x1 ← sid();~~
    ~~x2 ← sid();~~
    return ~~[x1,x2]~~ mysid;

    output doTx(msg)
      ~~ic~~ oc {...} ...
      x1.tx(msg);
      ~~oc~~ ic {...} ...
      return;

    output doRx()
      ~~ic~~ oc {...} ...
      msg ← x2.rx();
      ~~oc~~ ic {...} ...
      return ~~msg~~;

    atomicity assumption {...}
    progress ~~assumption~~ condition {...}
  }

Program Z for MsgImp and MsgService

- program Z(a1,a2) {
  ia {MsgService.ic}
  inputs(); outputs();
  [x1,x2] ← startSystem(MsgImp(a1,a2));
  si ← startSystem(MsgServiceInverse(a1,a2,[x1,x2]));
  return mysid;

  atomicity assumption {}
  progress assumption {weak fairness}
  }

- MsgImp(a1,a2) implements MsgService(a1,a2) if Z satisfies
  - Inv (thread t at si.doRx().ic) $\Rightarrow$ si.doRx().ic)
  - lsi.(progress condition)

Outline

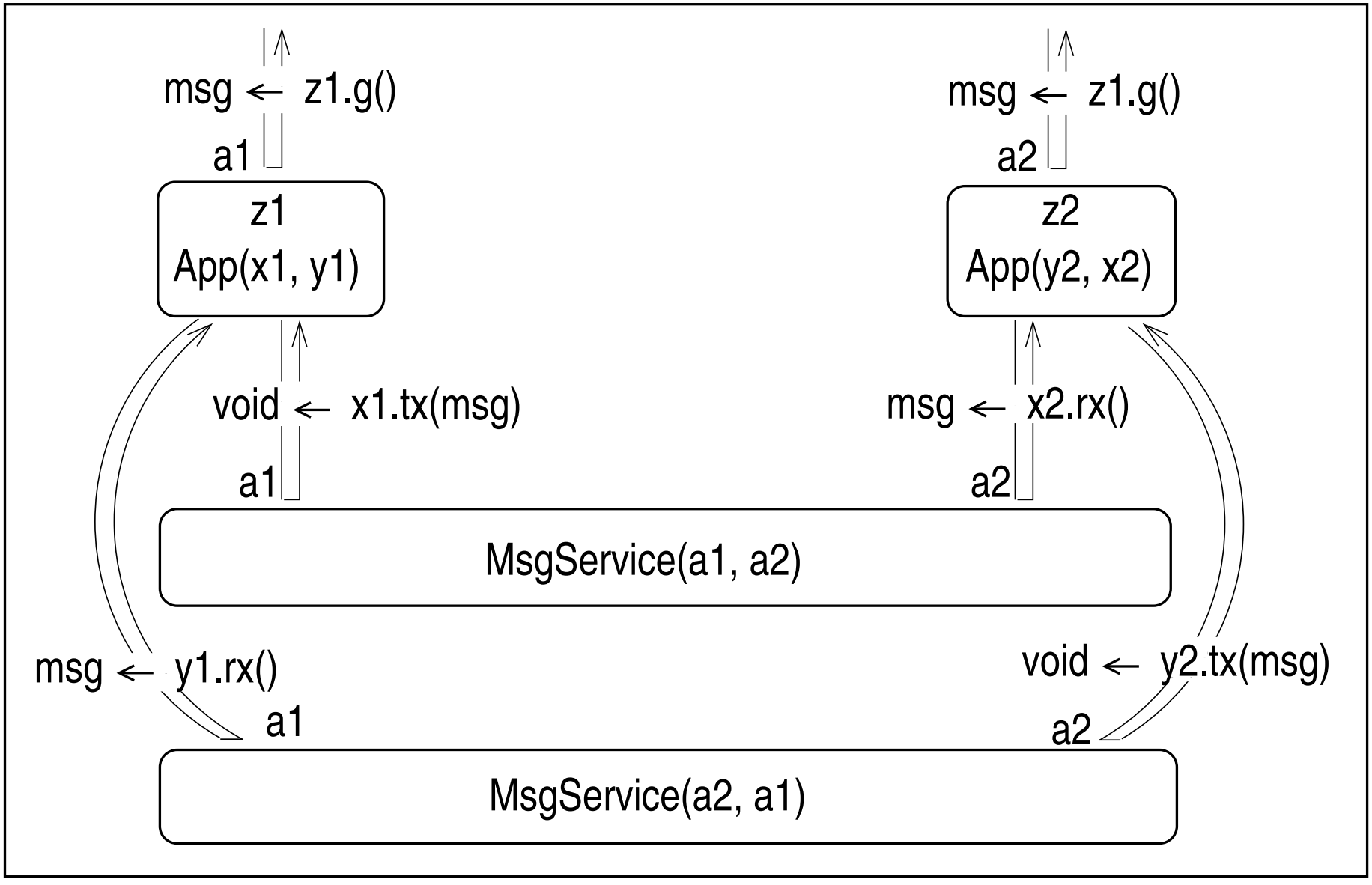
Using LockService

- program ProdCons1(J) {
  ia {...} // input assumption
  lck ← startSystem(~~Lock()~~ LockService());
  cons ← startSystem(Consumer(lck,J));
  prod ← startSystem(Producer(lck,cons,J));
  return mysid;

  atomicity assumption {} // none
  progress assumption {weak fairness for thread}
  }

- For proper use of service, need to prove
  - Inv (thread t at lck.acq.ic)
    $\Rightarrow$ lck.(not ending and t does not have lock)
  - Inv (thread t at lck.rel.ic)
    $\Rightarrow$ lck.(not ending and t has lock)

Using MsgService – 1



Using MsgService – 2

- ```
  program DistApp(a1, a2) {
    ia {...}        // input assumption
    [x1,x2] ← startSystem(MsgService(a1,a2));  // tx x1; rx x2
    [y2,y1] ← startSystem(MsgService(a2,a1));  // tx y2; rx y1
    z1 ← startSystem(App(x1,y1,a1,a2));
    z2 ← startSystem(App(y2,x2,a2,a1));
    return [z1,z2];

    atomicity assumption {}  // none
    progress assumption {weak fairness for thread}
  }
  ```

- For proper use of service, need to ensure that calls to services (x1.tx, x2.rx, y2.tx, y2.rx) satisfy their input conditions.
  ```