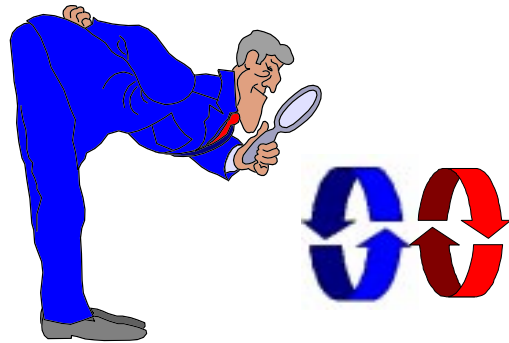


Safety & Liveness Properties



Concurrency: safety & liveness properties

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Concepts: **properties:** true for every possible execution
safety: nothing bad happens
liveness: something good *eventually* happens

Models: **safety:** no reachable **ERROR/STOP** state
progress: an action is *eventually* executed
 fair choice and action priority

Practice: threads and monitors

Aim: property satisfaction.

Concurrency: safety & liveness properties

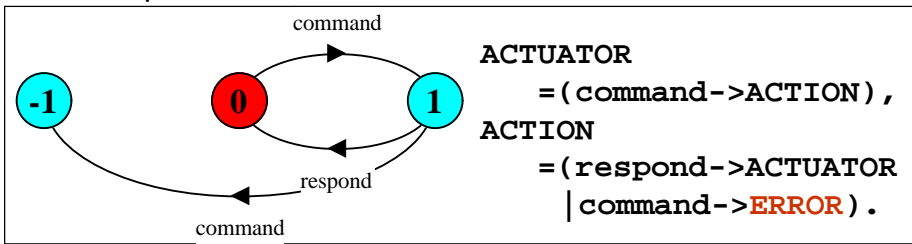
2

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7.1 Safety

A **safety** property asserts that nothing **bad** happens.

- ◆ **STOP** or deadlocked state (no outgoing transitions)
- ◆ **ERROR** process (-1) to detect erroneous behaviour



- ◆ analysis using *LTSA*: (shortest trace)

Trace to ERROR:
 command
 command

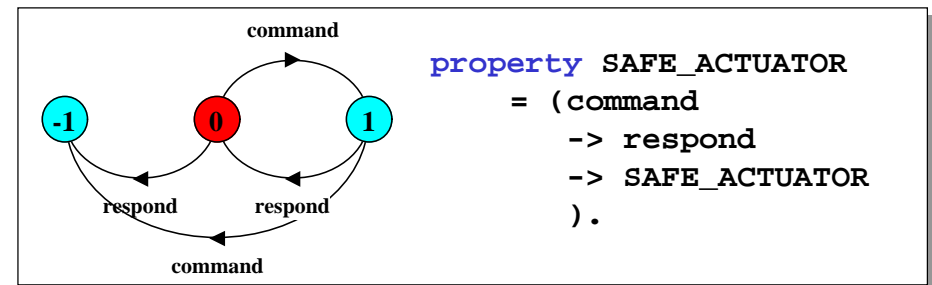
Concurrency: safety & liveness properties

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Safety - property specification

- ◆ **ERROR** conditions state what is **not** required (cf. exceptions).
- ◆ in complex systems, it is usually better to specify safety **properties** by stating directly what **is** required.



- ◆ analysis using *LTSA* as before.

Concurrency: safety & liveness properties

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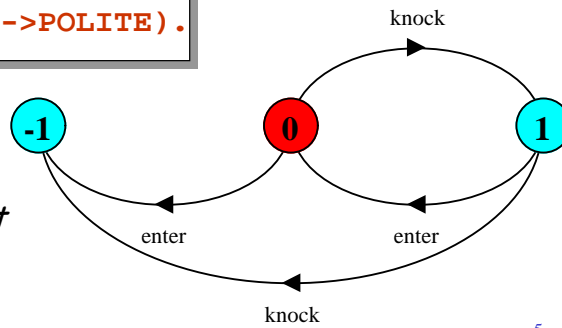
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Safety properties

Property that it is polite to knock before entering a room.

Traces: `knock→enter` ✓ `enter` ✗ `knock→knock`

```
property POLITE
= (knock->enter->POLITE).
```



In all states, all the actions in the alphabet of a property are eligible choices.

Concurrency: safety & liveness properties

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Safety properties

Safety property P defines a deterministic process that asserts that any trace including actions in the alphabet of P , is accepted by P .

Thus, if P is composed with s , then traces of actions in the alphabet of $s \cap$ alphabet of P must also be valid traces of P , otherwise **ERROR** is reachable.

Transparency of safety properties:

Since all actions in the alphabet of a property are eligible choices, composing a property with a set of processes does not affect their correct behavior. However, if a behavior can occur which violates the safety property, then **ERROR** is reachable. Properties must be deterministic to be transparent.

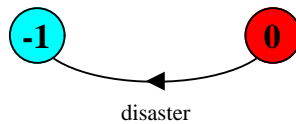
Concurrency: safety & liveness properties

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Safety properties

♦ How can we specify that some action, **disaster**, never occurs?



```
property CALM = STOP + {disaster}.
```

A safety property must be specified so as to include all the acceptable, valid behaviors in its alphabet.

Concurrency: safety & liveness properties

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Safety - mutual exclusion

```
LOOP = (mutex.down -> enter -> exit
        -> mutex.up -> LOOP).
|| SEMADEMO = (p[1..3]:LOOP
|| {p[1..3]}::mutex:SEMAPHORE(1)).
```

How do we check that this does indeed ensure mutual exclusion in the critical section?

```
property MUTEX = (p[i:1..3].enter
-> p[i].exit
-> MUTEX ).
|| CHECK = (SEMADEMO || MUTEX).
```

Check safety using LTSA.

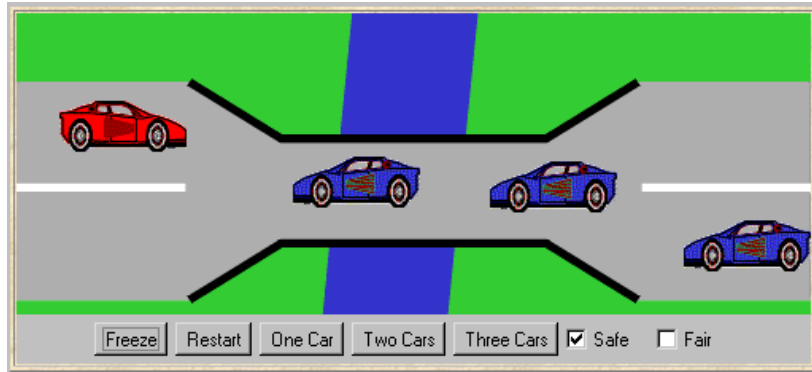
What happens if semaphore is initialized to 2?

Concurrency: safety & liveness properties

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7.2 Single Lane Bridge problem



A bridge over a river is only wide enough to permit a single lane of traffic. Consequently, cars can only move concurrently if they are moving in the **same direction**. A safety violation occurs if two cars moving in different directions enter the bridge at the same time.

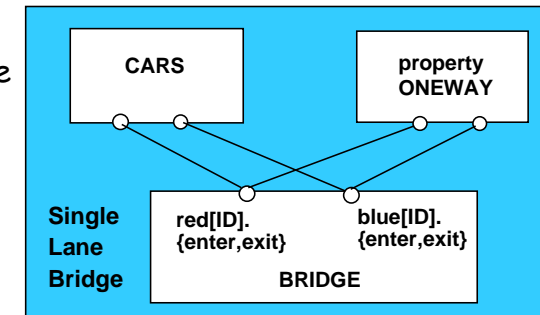
Concurrency: safety & liveness properties

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Single Lane Bridge - model

- ◆ Events or actions of interest?
enter and exit
- ◆ Identify processes.
cars and bridge
- ◆ Identify properties.
oneway
- ◆ Define each process and interactions (structure).



Concurrency: safety & liveness properties

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Single Lane Bridge - CARS model

```
const N = 3      // number of each type of car
range T = 0..N  // type of car count
range ID= 1..N  // car identities

CAR = (enter->exit->CAR).
```

To model the fact that cars cannot pass each other on the bridge, we model a CONVOY of cars in the same direction. We will have a red and a blue convoy of up to N cars for each direction:

```
|| CARS = (red:CONVOY || blue:CONVOY).
```

Concurrency: safety & liveness properties

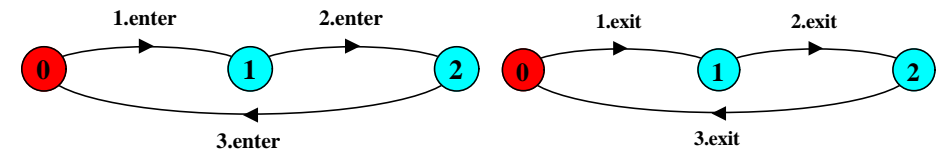
11

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Single Lane Bridge - CONVOY model

```
NOPASS1 = C[1],           //preserves entry order
C[i:ID] = ([i].enter-> C[i%N+1]).
NOPASS2 = C[1],           //preserves exit order
C[i:ID] = ([i].exit-> C[i%N+1]).

|| CONVOY = ([ID]:CAR || NOPASS1 || NOPASS2).
```



Permits 1.enter → 2.enter → 1.exit → 2.exit
but not 1.enter → 2.enter → 2.exit → 1.exit
ie. no overtaking.

Concurrency: safety & liveness properties

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Single Lane Bridge - BRIDGE model

Cars can move concurrently on the bridge only if in the **same direction**. The bridge maintains counts of **blue** and **red** cars on the bridge. **Red** cars are only allowed to enter when the **red** count is zero and vice-versa.

```
BRIDGE = BRIDGE[0][0], // initially empty
BRIDGE[nr:T][nb:T] = //nr is the red count, nb the blue
  (when(nb==0)
    red[ID].enter -> BRIDGE[nr+1][nb] //nb==0
  | red[ID].exit -> BRIDGE[nr-1][nb]
  |when(nr==0)
    blue[ID].enter-> BRIDGE[nr][nb+1] //nr==0
  | blue[ID].exit -> BRIDGE[nr][nb-1]
  ).
```

Even when 0, exit actions permit the car counts to be decremented. **LTSA** maps these undefined states to **ERROR**.

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Concurrency: safety & liveness properties

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Single Lane Bridge - safety property ONEWAY

We now specify a **safety** property to check that cars do not collide! While **red** cars are on the bridge only **red** cars can enter; similarly for **blue** cars. When the bridge is empty, either a **red** or a **blue** car may enter.

```
property ONEWAY = (red[ID].enter -> RED[1]
  | blue.[ID].enter -> BLUE[1]
  ),
RED[i:ID] = (red[ID].enter -> RED[i+1]
  |when(i==1)red[ID].exit -> ONEWAY
  |when(i>1) red[ID].exit -> RED[i-1]
  ), //i is a count of red cars on the bridge
BLUE[i:ID]= (blue[ID].enter-> BLUE[i+1]
  |when(i==1)blue[ID].exit -> ONEWAY
  |when(i>1)blue[ID].exit -> BLUE[i-1]
  ). //i is a count of blue cars on the bridge
```

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Single Lane Bridge - model analysis

||SingleLaneBridge = (CARS || BRIDGE | ONEWAY).

Is the safety property ONEWAY violated?

No deadlocks/errors

||SingleLaneBridge = (CARS | ONEWAY).

Without the BRIDGE constraints, is the safety property ONEWAY violated?

Trace to property violation in ONEWAY:
red.1.enter
blue.1.enter

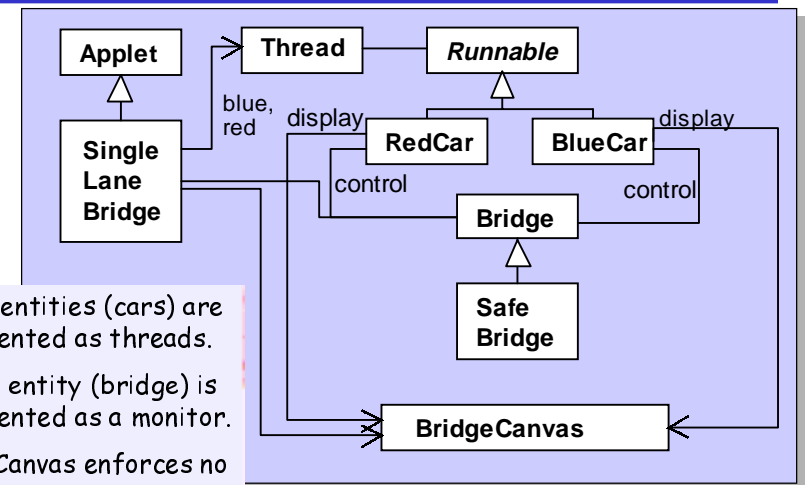
15

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Single Lane Bridge - implementation in Java

Active entities (cars) are implemented as threads.
Passive entity (bridge) is implemented as a monitor.
BridgeCanvas enforces no overtaking.



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Concurrency: safety & liveness properties

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Single Lane Bridge - BridgeCanvas

An instance of `BridgeCanvas` class is created by `SingleLaneBridge` applet - `ref` is passed to each newly created `RedCar` and `BlueCar` object.

```
class BridgeCanvas extends Canvas {
    public void init(int ncars) {...} //set number of cars
    //move red car with the identity i a step
    //returns true for the period from just before, until just after car on bridge
    public boolean moveRed(int i)
        throws InterruptedException {...}
    //move blue car with the identity i a step
    //returns true for the period from just before, until just after car on bridge
    public boolean moveBlue(int i)
        throws InterruptedException {...}
    public synchronized void freeze(){...} //freeze display
    public synchronized void thaw(){...} //unfreeze display
}
```

Concurrency: safety & liveness properties

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Single Lane Bridge - RedCar

```
class RedCar implements Runnable {
    BridgeCanvas display; Bridge control; int id;
    RedCar(Bridge b, BridgeCanvas d, int id) {
        display = d; this.id = id; control = b;
    }
    public void run() {
        try {
            while(true) {
                while (!display.moveRed(id)); // not on bridge
                control.redEnter(); // request access to bridge
                while (display.moveRed(id)); // move over bridge
                control.redExit(); // release access to bridge
            }
        } catch (InterruptedException e) {}
    }
}
```

Similarly for the `BlueCar`

Concurrency: safety & liveness properties

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Single Lane Bridge - class Bridge

```
class Bridge {
    synchronized void redEnter()
        throws InterruptedException {}
    synchronized void redExit() {}
    synchronized void blueEnter()
        throws InterruptedException {}
    synchronized void blueExit() {}
}
```

Class `Bridge` provides a null implementation of the access methods i.e. no constraints on the access to the bridge.

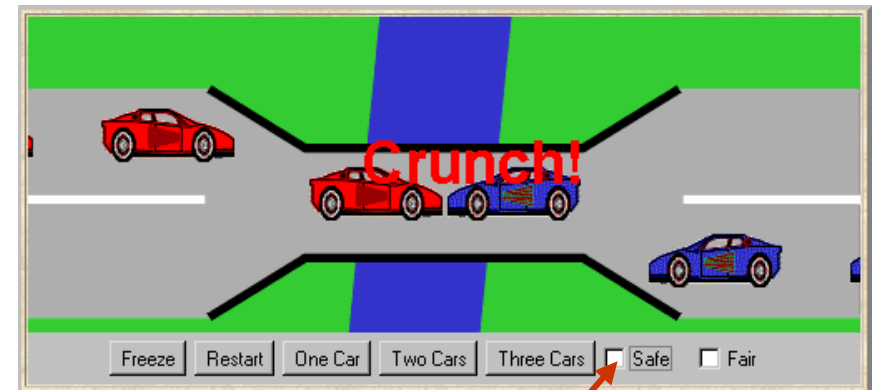
Result..... ?

Concurrency: safety & liveness properties

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Single Lane Bridge



To ensure safety, the "safe" check box must be chosen in order to select the `SafeBridge` implementation.

Concurrency: safety & liveness properties

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Single Lane Bridge - SafeBridge

```
class SafeBridge extends Bridge {
    private int nred = 0; //number of red cars on bridge
    private int nblue = 0; //number of blue cars on bridge

    // Monitor Invariant:  nred ≥ 0 and nblue ≥ 0 and
    //                    not (nred > 0 and nblue > 0)

    synchronized void redEnter()
        throws InterruptedException {
        while (nblue > 0) wait();
        ++nred;
    }

    synchronized void redExit(){
        --nred;
        if (nred == 0) notifyAll();
    }
}
```

This is a direct translation from the BRIDGE model.

Single Lane Bridge - SafeBridge

```
synchronized void blueEnter()
    throws InterruptedException {
    while (nred > 0) wait();
    ++nblue;
}

synchronized void blueExit(){
    --nblue;
    if (nblue == 0) notifyAll();
}
```

To avoid unnecessary thread switches, we use *conditional notification* to wake up waiting threads only when the number of cars on the bridge is zero i.e. when the last car leaves the bridge.

But does every car eventually get an opportunity to cross the bridge? This is a liveness property.

7.3 Liveness

A **safety** property asserts that nothing **bad** happens.

A **liveness** property asserts that something **good** eventually happens.

Single Land Bridge: *Does every car eventually get an opportunity to cross the bridge?*

ie. make **PROGRESS?**

A **progress** property asserts that it is *always* the case that an action is *eventually* executed. **Progress** is the opposite of **starvation**, the name given to a concurrent programming situation in which an action is never executed.

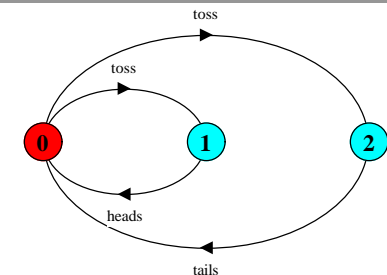
Progress properties - fair choice

Fair Choice: If a choice over a set of transitions is executed infinitely often, then every transition in the set will be executed infinitely often.

If a coin were tossed an infinite number of times, we would expect that heads would be chosen infinitely often and that tails would be chosen infinitely often.

This requires **Fair Choice** !

```
COIN = (toss->heads->COIN
        | toss->tails->COIN).
```



Progress properties

progress $P = \{a_1, a_2 \dots a_n\}$ defines a progress property P which asserts that in an infinite execution of a target system, at least **one** of the actions $a_1, a_2 \dots a_n$ will be executed infinitely often.

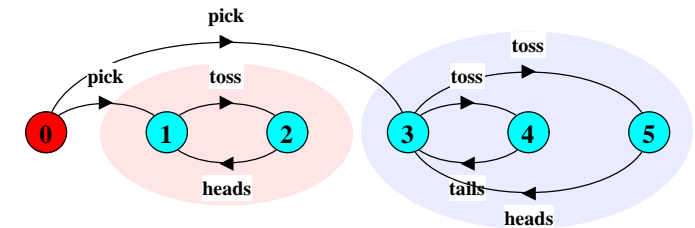
➡ COIN system: progress HEADS = {heads} ✓
 progress TAILS = {tails} ✓

LTSA check progress: No progress violations detected.

Progress properties

Suppose that there were two possible coins that could be picked up:

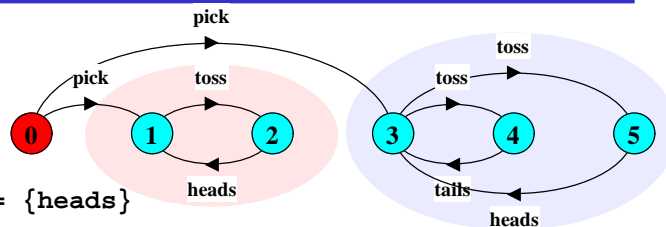
a **trick coin** and a **regular coin**.....



TWOCOIN = (pick->COIN | pick->TRICK),
 TRICK = (toss->heads->TRICK),
 COIN = (toss->heads->COIN | toss->tails->COIN).

➡ TWOCOIN: progress HEADS = {heads} ✓
 progress TAILS = {tails} ✗

Progress properties



progress HEADS = {heads}

progress TAILS = {tails}

LTSA check progress ➡

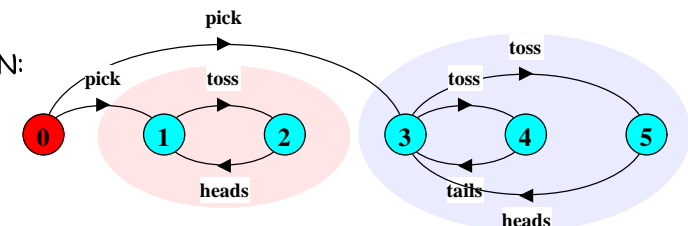
Progress violation: TAILS
 Path to terminal set of states:
 pick
 Actions in terminal set:
 {toss, heads}

progress HEADS or Tails = {heads, tails} ✓

Progress analysis

A **terminal set of states** is one in which every state is reachable from every other state in the set via one or more transitions, and there is no transition from within the set to any state outside the set.

Terminal sets for TWOCOIN:
 {1,2} and {3,4,5}



Given **fair choice**, each terminal set represents an execution in which each action used in a transition in the set is executed infinitely often.

Since there is no transition out of a terminal set, any action that is **not** used in the set cannot occur infinitely often in all executions of the system - and hence represents a **potential progress violation!**

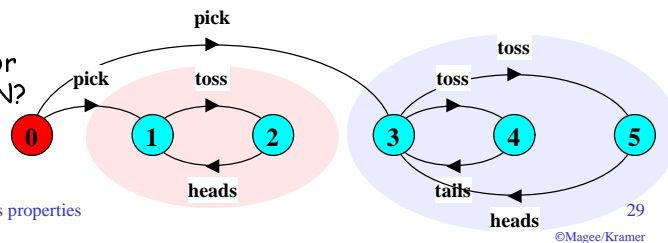
Progress analysis

A progress property is **violated** if analysis finds a terminal set of states in which **none** of the progress set actions appear.

➡ progress TAILS = {tails} in {1,2}

Default: given fair choice, for *every* action in the alphabet of the target system, that action will be executed infinitely often. This is equivalent to specifying a *separate progress property for every action*.

➡ Default analysis for TWOCOIN?



Concurrency: safety & liveness properties

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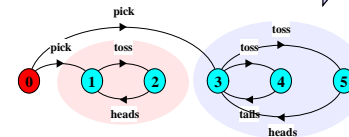
Progress analysis

Default analysis for TWOCOIN: *separate progress property for every action*.

➡ and ➡

Progress violation for actions: {pick}
Path to terminal set of states: pick
Actions in terminal set: {toss, heads, tails}

Progress violation for actions: {pick, tails}
Path to terminal set of states: pick
Actions in terminal set: {toss, heads}



If the default holds, then every other progress property holds i.e. every action is executed infinitely often and system consists of a single terminal set of states.

Concurrency: safety & liveness properties

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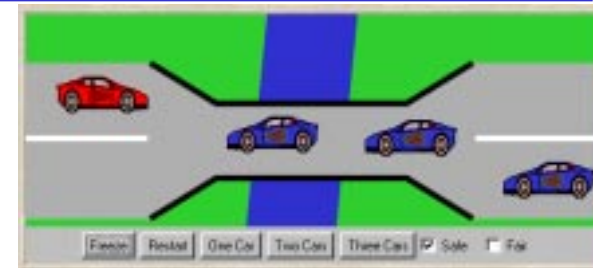
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Progress - single lane bridge

The Single Lane Bridge implementation can permit progress violations.

However, if default progress analysis is applied to the model then **no** violations are detected!

Why not?



➡ progress BLUECROSS = {blue[ID].enter}
progress REDCROSS = {red[ID].enter}
No progress violations detected.

Fair choice means that eventually every possible execution occurs, including those in which cars do not starve. To detect progress problems we must superimpose some **scheduling policy** for actions, which models the situation in which the bridge is **congested**.

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Progress - action priority

Action priority expressions describe scheduling properties:

High Priority
(" << ")

$P || C = (P || Q) << \{a_1, \dots, a_n\}$ specifies a composition in which the actions a_1, \dots, a_n have **higher** priority than any other action in the alphabet of $P || Q$ including the silent action τ . *In any choice in this system which has one or more of the actions a_1, \dots, a_n labeling a transition, the transitions labeled with lower priority actions are discarded.*

Low Priority
(" >> ")

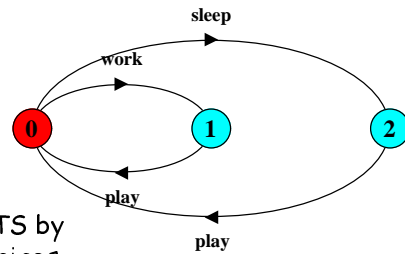
$P || C = (P || Q) >> \{a_1, \dots, a_n\}$ specifies a composition in which the actions a_1, \dots, a_n have **lower** priority than any other action in the alphabet of $P || Q$ including the silent action τ . *In any choice in this system which has one or more transitions not labeled by a_1, \dots, a_n , the transitions labeled by a_1, \dots, a_n are discarded.*

Concurrency: safety &

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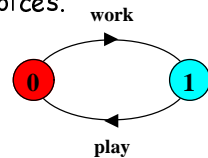
Progress - action priority

```
NORMAL = (work->play->NORMAL
|sleep->play->NORMAL).
```

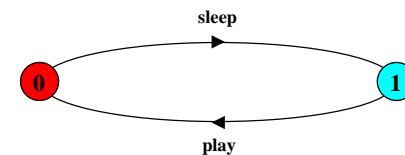


Action priority simplifies the resulting LTS by discarding lower priority actions from choices.

```
||HIGH = (NORMAL) << {work}.
```



```
||LOW = (NORMAL) >> {work}.
```



Concurrency: safety & liveness properties

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7.4 Congested single lane bridge

```
progress BLUECROSS = {blue[ID].enter}
progress REDCROSS = {red[ID].enter}
```

BLUECROSS - eventually one of the **blue** cars will be able to enter

REDCROSS - eventually one of the **red** cars will be able to enter

➔ Congestion using action priority?

Could give **red** cars priority over **blue** (or vice versa)?
In practice neither has priority over the other.

Instead we merely encourage congestion by *lowering the priority of the exit actions of both cars from the bridge.*

```
||CongestedBridge = (SingleLaneBridge)
>>{red[ID].exit, blue[ID].exit}.
```

➔ Progress Analysis? LTS?

Concurrency: safety & liveness properties

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congested single lane bridge model

Progress violation: BLUECROSS

Path to terminal set of states:

```
red.1.enter
red.2.enter
```

Actions in terminal set:

```
{red.1.enter, red.1.exit, red.2.enter,
red.2.exit, red.3.enter, red.3.exit}
```

Progress violation: REDCROSS

Path to terminal set of states:

```
blue.1.enter
blue.2.enter
```

Actions in terminal set:

```
{blue.1.enter, blue.1.exit, blue.2.enter,
blue.2.exit, blue.3.enter, blue.3.exit}
```

This corresponds with the observation that, with *more than one car*, it is possible that whichever color car enters the bridge first will continuously occupy the bridge preventing the other color from ever crossing.

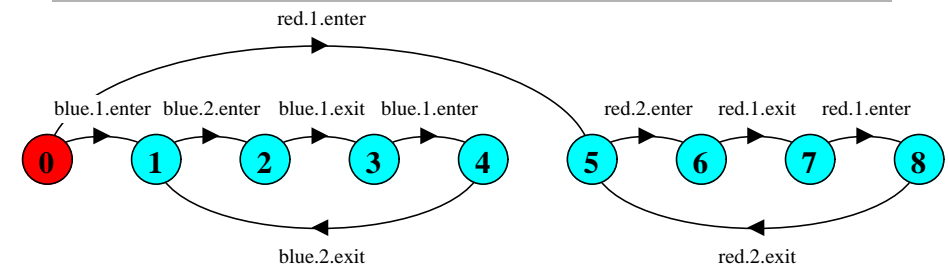
Concurrency: safety & liveness properties

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congested single lane bridge model

```
||CongestedBridge = (SingleLaneBridge)
>>{red[ID].exit, blue[ID].exit}.
```



Will the results be the same if we model congestion by giving car entry to the bridge high priority?

Can congestion occur if there is only one car moving in each direction?

Concurrency: safety & liveness properties

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Progress - revised single lane bridge model

The bridge needs to know whether or not cars are **waiting** to cross.

Modify CAR:

```
CAR = (request->enter->exit->CAR).
```

Modify BRIDGE:

Red cars are only allowed to enter the bridge if there are no **blue** cars on the bridge **and** there are **no blue cars waiting** to enter the bridge.

Blue cars are only allowed to enter the bridge if there are no **red** cars on the bridge **and** there are **no red cars waiting** to enter the bridge.

Progress - revised single lane bridge model

```
/* nr- number of red cars on the bridge wr - number of red cars waiting to enter
   nb- number of blue cars on the bridge wb - number of blue cars waiting to enter
*/
BRIDGE = BRIDGE[0][0][0][0],
BRIDGE[nr:T][nb:T][wr:T][wb:T] =
  (red[ID].request -> BRIDGE[nr][nb][wr+1][wb]
  |when (nb==0 && wb==0)
    red[ID].enter -> BRIDGE[nr+1][nb][wr-1][wb]
  |red[ID].exit -> BRIDGE[nr-1][nb][wr][wb]
  |blue[ID].request -> BRIDGE[nr][nb][wr][wb+1]
  |when (nr==0 && wr==0)
    blue[ID].enter -> BRIDGE[nr][nb+1][wr][wb-1]
  |blue[ID].exit -> BRIDGE[nr][nb-1][wr][wb]
  ).
```

OK now?

Progress - analysis of revised single lane bridge model

Trace to DEADLOCK:

```
red.1.request
red.2.request
red.3.request
blue.1.request
blue.2.request
blue.3.request
```

The trace is the scenario in which there are cars waiting at both ends, and consequently, the bridge does not allow either red or blue cars to enter.

Solution?

Introduce some **asymmetry** in the problem (cf. Dining philosophers).

This takes the form of a boolean variable (**bt**) which breaks the deadlock by indicating whether it is the turn of **blue** cars or **red** cars to enter the bridge.

Arbitrarily set **bt** to true initially giving **blue** initial precedence.

Progress - 2nd revision of single lane bridge model

```
const True = 1
const False = 0
range B = False..True
/* bt - true indicates blue turn, false indicates red turn */
BRIDGE = BRIDGE[0][0][0][0][True],
BRIDGE[nr:T][nb:T][wr:T][wb:T][bt:B] =
  (red[ID].request -> BRIDGE[nr][nb][wr+1][wb][bt]
  |when (nb==0 && (wb==0 | !bt))
    red[ID].enter -> BRIDGE[nr+1][nb][wr-1][wb][bt]
  |red[ID].exit -> BRIDGE[nr-1][nb][wr][wb][True]
  |blue[ID].request -> BRIDGE[nr][nb][wr][wb+1][bt]
  |when (nr==0 && (wr==0 | bt))
    blue[ID].enter -> BRIDGE[nr][nb+1][wr][wb-1][bt]
  |blue[ID].exit -> BRIDGE[nr][nb-1][wr][wb][False]
  ).
```

⇒ **Analysis?**

Revised single lane bridge implementation - FairBridge

```
class FairBridge extends Bridge {
    private int nred = 0; //count of red cars on the bridge
    private int nblue = 0; //count of blue cars on the bridge
    private int waitblue = 0; //count of waiting blue cars
    private int waitred = 0; //count of waiting red cars
    private boolean blueturn = true;

    synchronized void redEnter()
        throws InterruptedException {
        ++waitred;
        while (nblue>0 || (waitblue>0 && !blueturn)) wait();
        --waitred;
        ++nred;
    }

    synchronized void redExit(){
        --nred;
        blueturn = true;
        if (nred==0)notifyAll();
    }
}
```

This is a direct translation from the model.

Revised single lane bridge implementation - FairBridge

```
synchronized void blueEnter(){
    throws InterruptedException {
    ++waitblue;
    while (nred>0 || (waitred>0 && !blueturn)) wait();
    --waitblue;
    ++nblue;
}

synchronized void blueExit(){
    --nblue;
    blueturn = false;
    if (nblue==0) notifyAll();
}
}
```

The "fair" check box must be chosen in order to select the FairBridge implementation.

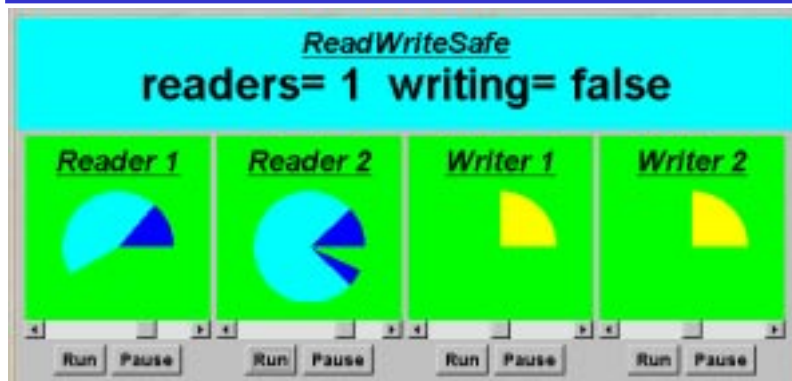
Note that we did not need to introduce a new request monitor method. The existing enter methods can be modified to increment a wait count before testing whether or not the caller can access the bridge.

Concurrency: safety & liveness properties

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7.5 Readers and Writers



Light blue indicates database access.

A shared database is accessed by two kinds of processes. **Readers** execute transactions that examine the database while **Writers** both examine and update the database. A Writer must have exclusive access to the database; any number of Readers may concurrently access it.

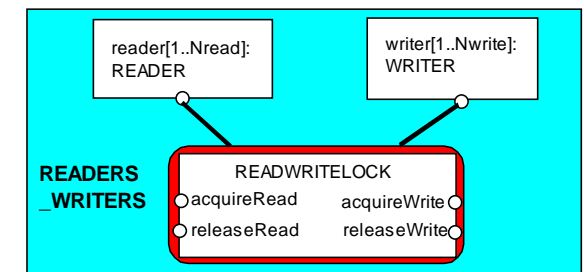
Concurrency: safety & liveness properties

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readers/writers model

- ◆ Events or actions of interest?
 - acquireRead, releaseRead, acquireWrite, releaseWrite
- ◆ Identify processes.
 - Readers, Writers & the RW_Lock
- ◆ Identify properties.
 - RW_Safe
 - RW_Progress
- ◆ Define each process and interactions (structure).



Concurrency: safety & liveness properties

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readers/writers model - READER & WRITER

```

set Actions =
  {acquireRead,releaseRead,acquireWrite,releaseWrite}

READER = (acquireRead->examine->releaseRead->READER)
  + Actions
  \ {examine}.

WRITER = (acquireWrite->modify->releaseWrite->WRITER)
  + Actions
  \ {modify}.
  
```

Alphabet extension is used to ensure that the other access actions cannot occur freely for any prefixed instance of the process (as before).

Action hiding is used as actions `examine` and `modify` are not relevant for access synchronisation.

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readers/writers model - RW_LOCK

```

const False = 0    const True  = 1
range Bool   = False..True
const Nread  = 2    // Maximum readers
const Nwrite = 2    // Maximum writers

RW_LOCK = RW[0][False],
RW[readers:0..Nread][writing:Bool] =
  (when (!writing)
    acquireRead  -> RW[readers+1][writing]
  | releaseRead  -> RW[readers-1][writing]
  | when (readers==0 && !writing)
    acquireWrite -> RW[readers][True]
  | releaseWrite -> RW[readers][False]
  ).
  
```

The lock maintains a count of the number of readers, and a Boolean for the writers.

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readers/writers model - safety

```

property SAFE_RW
  = (acquireRead  -> READING[1]
    | acquireWrite -> WRITING
    ),
  READING[i:1..Nread]
  = (acquireRead -> READING[i+1]
    | when(i>1) releaseRead -> READING[i-1]
    | when(i==1) releaseRead -> SAFE_RW
    ),
  WRITING = (releaseWrite -> SAFE_RW).
  
```

We can check that RW_LOCK satisfies the safety property.....

```
|| READWRITELOCK = (RW_LOCK || SAFE_RW).
```

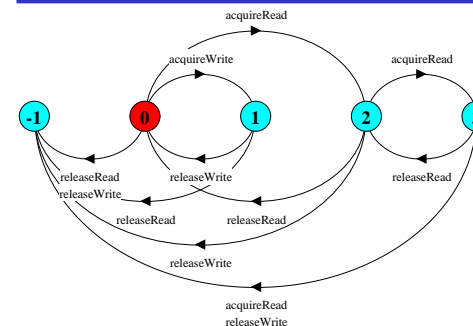
➡ **Safety Analysis? LTS?**

Concurrency: safety & liveness properties

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readers/writers model



An **ERROR** occurs if a reader or writer is badly behaved (release before acquire or more than two readers).

We can now compose the **READWRITELOCK** with **READER** and **WRITER** processes according to our structure... ..

```

|| READERS_WRITERS
  = (reader[1..Nread] :READER
    || writer[1..Nwrite]:WRITER
    || {reader[1..Nread],
        writer[1..Nwrite]}::READWRITELOCK).
  
```

➡ **Safety and Progress Analysis?**

Concurrency: safety & liveness properties

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readers/writers - progress

```
progress WRITE = {writer[1..Nwrite].acquireWrite}
progress READ  = {reader[1..Nread].acquireRead}
```

WRITE - eventually one of the **writers** will acquireWrite

READ - eventually one of the **readers** will acquireRead

➔ Adverse conditions using action priority?

we lower the priority of the release actions for both **readers** and **writers**.

```
|| RW_PROGRESS = READERS_WRITERS
   >>{reader[1..Nread].releaseRead,
      writer[1..Nread].releaseWrite}.
```

➔ Progress Analysis? LTS?

Concurrency: safety & liveness properties

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readers/writers model - progress

Progress violation: WRITE

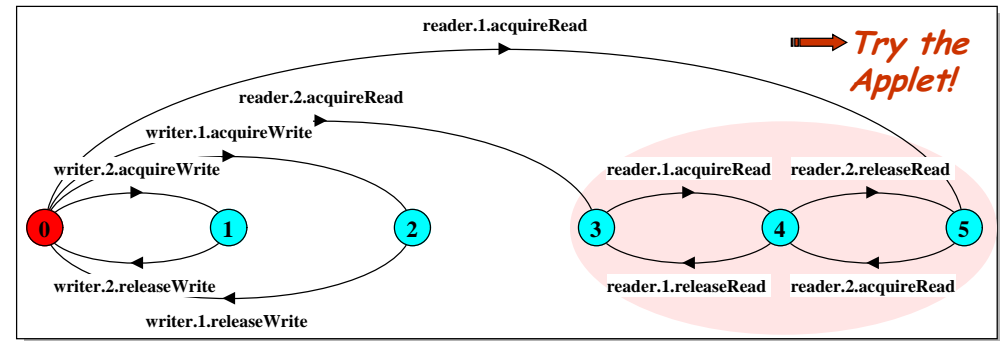
Path to terminal set of states:

reader.1.acquireRead

Actions in terminal set:

```
{reader.1.acquireRead, reader.1.releaseRead,
 reader.2.acquireRead, reader.2.releaseRead}
```

Writer starvation:
The number of **readers** never drops to zero.



readers/writers implementation - monitor interface

We concentrate on the monitor implementation:

```
interface ReadWrite {
    public void acquireRead()
        throws InterruptedException;
    public void releaseRead();
    public void acquireWrite()
        throws InterruptedException;
    public void releaseWrite();
}
```

We define an **interface** that identifies the monitor methods that must be implemented, and develop a number of alternative implementations of this interface.

Firstly, the **safe** READWRITELOCK.

Concurrency: safety & liveness properties

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readers/writers implementation - ReadWriteSafe

```
class ReadWriteSafe implements ReadWrite {
    private int readers = 0;
    private boolean writing = false;

    public synchronized void acquireRead()
        throws InterruptedException {
        while (writing) wait();
        ++readers;
    }

    public synchronized void releaseRead() {
        --readers;
        if (readers == 0) notify();
    }
}
```

Unblock a **single writer** when no more readers.

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readers/writers implementation - ReadWriteSafe

```
public synchronized void acquireWrite()
    throws InterruptedException {
    while (readers>0 || writing) wait();
    writing = true;
}

public synchronized void releaseWrite() {
    writing = false;
    notifyAll();
}
}
```

Unblock **all readers**

However, this monitor implementation suffers from the WRITE progress problem: possible *writer starvation* if the number of **readers** never drops to zero.

➡ **Solution?**

readers/writers - writer priority



Strategy:
Block readers
if there is a
writer waiting.

```
set Actions = {acquireRead,releaseRead,acquireWrite,
               releaseWrite,requestWrite}
```

```
WRITER =(requestWrite->acquireWrite->modify
         ->releaseWrite->WRITER
         )+Actions\{modify}.
```

readers/writers model - writer priority

```
RW_LOCK = RW[0][False][0],
RW[readers:0..Nread][writing:Bool][waitingW:0..Nwrite]
= (when (!writing && waitingW==0)
   acquireRead -> RW[readers+1][writing][waitingW]
 | releaseRead -> RW[readers-1][writing][waitingW]
 | when (readers==0 && !writing)
   acquireWrite-> RW[readers][True][waitingW-1]
 | releaseWrite-> RW[readers][False][waitingW]
 | requestWrite-> RW[readers][writing][waitingW+1]
 ).
```

➡ **Safety and Progress Analysis ?**

readers/writers model - writer priority

property RW_SAFE:

No deadlocks/errors

progress READ and WRITE:

```
Progress violation: READ
Path to terminal set of states:
  writer.1.requestWrite
  writer.2.requestWrite
Actions in terminal set:
{writer.1.requestWrite, writer.1.acquireWrite,
 writer.1.releaseWrite, writer.2.requestWrite,
 writer.2.acquireWrite, writer.2.releaseWrite}
```

Reader starvation:
if always a
writer
waiting.

In practice, this may be satisfactory as is usually more read access than write, and readers generally want the most up to date information.

readers/writers implementation - ReadWritePriority

```
class ReadWritePriority implements ReadWrite{
    private int readers = 0;
    private boolean writing = false;
    private int waitingW = 0; // no of waiting Writers.

    public synchronized void acquireRead()
        throws InterruptedException {
        while (writing || waitingW>0) wait();
        ++readers;
    }

    public synchronized void releaseRead() {
        --readers;
        if (readers==0) notify();
    }
}
```

Concurrency: safety & liveness properties

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readers/writers implementation - ReadWritePriority

```
synchronized public void acquireWrite() {
    ++waitingW;
    while (readers>0 || writing) try{ wait();}
    catch(InterruptedException e){}
    --waitingW;
    writing = true;
}

synchronized public void releaseWrite() {
    writing = false;
    notifyAll();
}
}
```

*Both READ and WRITE progress properties can be satisfied by introducing a **turn** variable as in the Single Lane Bridge.*

Concurrency: safety & liveness properties

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Summary

◆ Concepts

- **properties:** true for every possible execution
- **safety:** nothing bad happens
- **liveness:** something good *eventually* happens

◆ Models

- **safety:** no reachable **ERROR/STOP** state
compose safety properties at appropriate stages
- **progress:** an action is eventually executed
fair choice and action priority
apply progress check on the final target system model

◆ Practice

- threads and monitors

Aim: property satisfaction

Concurrency: safety & liveness properties

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