# Safety and Liveness

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Reading material: Chapter 7 of Textbook.



## safety & liveness properties

**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

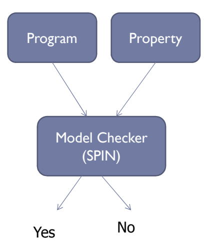
fair choice and action priority

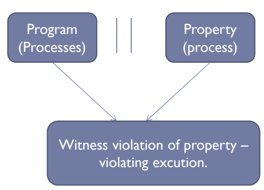
**Practice:** threads and monitors

**Aim: property satisfaction.**



## Programs, Properties




A desired property is supposed to hold true for all the concurrent program executions.



## So, what is a property?

- An attribute of the program that is true for *every* possible execution of the program.
- Have we seen any properties yet, in our discussion?
  - Yes, deadlocks – discussed last week
    - The property you want your concurrent program to preserve is the absence of deadlocks!
  - Mutual exclusion – discussed all through the lectures!
- Both no-deadlock and mutual exclusion are special cases of safety properties – something "bad" will not happen!
  - No deadlock will ever happen.
  - No two processes will ever be in the critical section.



## Liveness properties

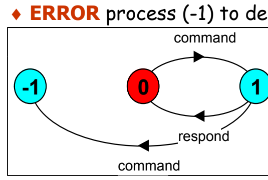
- Something "good" will eventually happen.
- The most common liveness property in seq. programs
  - The program will eventually terminate!
- For concurrent programs, liveness properties can be of the form
  - Request for shared resources are eventually granted.
- So, what is new in today's lecture's discussion?
  - We have been discussing properties like mutual exclusion all along. Today's discussion makes it more systematic and shows mutual excl. as a special case of a larger class of properties!



## 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




**ACTUATOR**
**=(command->ACTION),**
**ACTION**
**=(respond->ACTUATOR**
**|command->ERROR).**

**Trace to ERROR:**
**command**
**command**

## Safety Property Specification

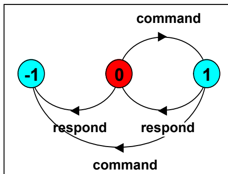
- Either, mark the violation of the safety property as "Error" states in the concurrent system S
  - Checking the safety property then amounts to checking that the "error" states are never reached.
- Instead, the safety property itself could be described as a process P (using our process equations).
  - Checking for property violation amounts to finding a trace of S that does not satisfy P.



## 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.




```
property SAFE_ACTUATOR
    = (command
        -> respond
        -> SAFE_ACTUATOR
        ).
```

A violation of this property is a trace which will lead to -1. We have to check whether such a trace is possible in the concurrent system being checked.



## Safety properties

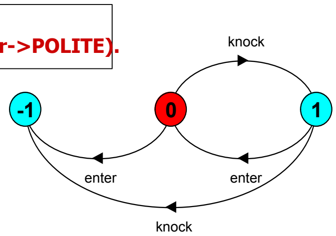
Property that it is polite to knock before entering a room.

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.*






## 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**.

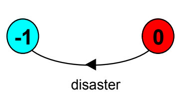
Thus, if **P** is composed with **S**, then traces of actions in the alphabet of **S** ∩ alphabet of **P** must also be valid traces of **P**, otherwise **ERROR** is reachable.

***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.*



## Safety properties

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




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



## Safety - mutual exclusion

```
LOOP = (mutex.down -> enter -> exit
                   -> mutex.up -> LOOP).
SEMADEMO = (p[1..3]:LOOP
            ||{p[1..3]}::mutex:SEMA(1)).
SEMA(v) = (up -> SEMA[v+1]
           | when (v > 0) down  ->SEMA[v-1]
           )
```

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

## Safety - mutual exclusion

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

*What happens if semaphore is initialized to 2?*



## Semphore - continued

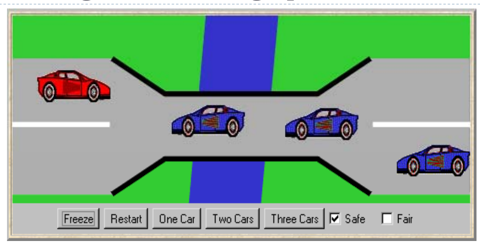
- Semaphore initialized to 2.

```
LOOP = (mutex.down -> enter -> exit
                   -> mutex.up -> LOOP).
SEMADEMO = (p[1..3]:LOOP
         ||{p[1..3]}::mutex:SEMA(1)).
SEMA(v) = (up -> SEMA[v+1]
          | when (v > 0) down ->SEMA[v-1]
          )
```

- Violation of MUTEX
  - p.1.mutex.down,p.1.enter, p.2.mutex.down, p.2.enter



## 7.2 Single Lane Bridge problem

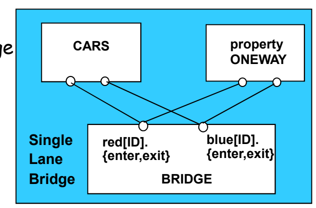



A bridge over a river is only wide enough to permit a single lane of traffic. Consequently, cars can only move concurrently if they are moving in the same direction. A safety violation occurs if two cars moving in different directions enter the bridge at the same time.



## 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).






## 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).
```

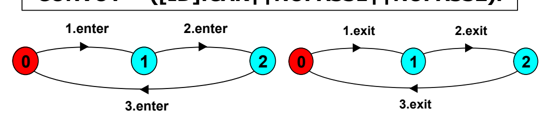
To model the fact that cars cannot pass each other on the bridge, we model a **CONVOY** of cars in the same direction. We will have a red and a blue convoy of up to N cars for each direction:

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



## Single Lane Bridge - CONVOY model

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

## 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 blue 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.*



## 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
```



## Single Lane Bridge - model analysis

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

*Is the safety property* **ONEWAY** *violated?*

**No deadlocks/errors**

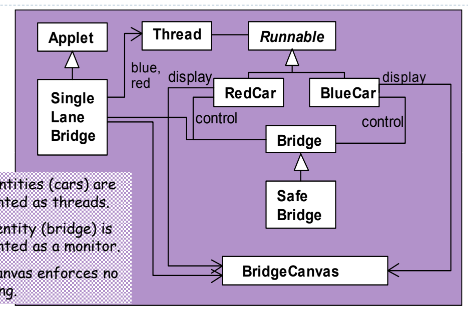
**SingleLaneBridge1 = (CARS||ONEWAY).**

*Without the* **BRIDGE** *contraints, is the safety property* **ONEWAY** *violated?*

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



## 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.



## 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 on bridge, from just before until just after
  public boolean moveRed(int i)
        throws InterruptedException{…}

  //move blue car with the identity i a step
  //returns true for the period on bridge, from just before until just after
  public boolean moveBlue(int i)
        throws InterruptedException{…}

  public synchronized void freeze(){…}// freeze display
  public synchronized void thaw(){…}  //unfreeze display
}
```



## 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

## Single Lane Bridge - class `Bridge`

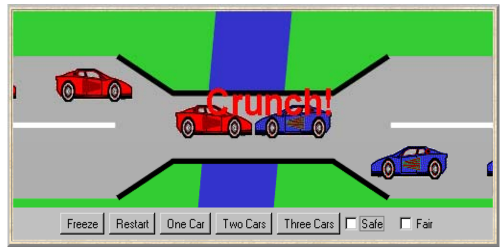
```
class Bridge {
  synchronized void redEnter()
        throws InterruptedException {}
  synchronized void redExit()  {}
  synchronized void blueEnter()
        throws InterruptedException {}
  synchronized void blueExit() {}
}
```

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

***Result………… ?***



## Single Lane Bridge




This bridge code is not safe.

We now present the **SafeBridge** implementation.



## 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 Lane 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 a specific action is *eventually* executed. Progress is the opposite of *starvation*, the name given to a concurrent programming situation in which a specific action is never executed.



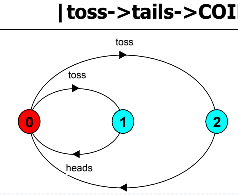
## Progress properties - fair choice

**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 = {a1,a2..an}** defines a progress property **P** which asserts that in an infinite execution of a target system, at least **one** of the actions **a1,a2..an** will be executed infinitely often.

COIN system: **progress HEADS = {heads}** ✓

**progress TAILS = {tails}** ? ✓

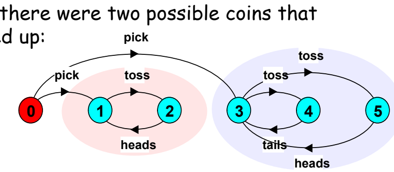
**No progress violations detected**
(assuming fair choice).



## 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}** ? ✗



## Further explanation

TWOCOIN: **progress HEADS = {heads} YES**

**progress TAILS = {tails} ? NO**

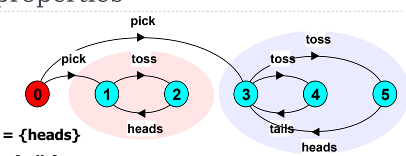
progress {heads}
case 1: if the trick coin is picked, only heads is executed
case 2: if the normal coin is picked, heads is still executed infinitely often assuming fair choice being exerted on the coin toss.

progress {tails}
case 1: if trick coin is picked, tails is never executed, violation of progress.

Note that we consider both possibilities of trick coin or normal coin being picked --- this is a choice which is made only once, not infinitely many times.



## Progress properties




**progress HEADS = {heads}**

**progress TAILS = {tails}**

***Violation of*** progress

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

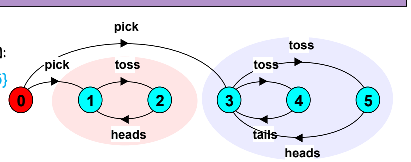
**progress HEADS or TAILS = {heads,tails}** ? ✓



## 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!



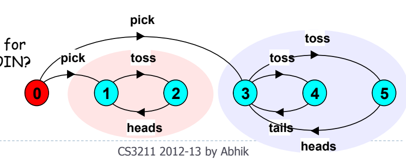
## Progress analysis

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?



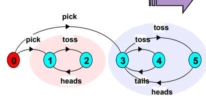
## Progress analysis

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

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

and

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

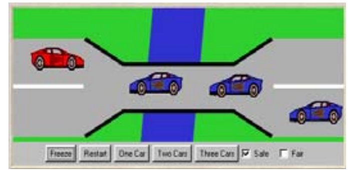



*If the default holds, then every other progress property holds i.e. every action is executed infinitely often and system consists of a single terminal set of states.*



## 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.**



## Why no progress violation is detected?

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

So, for every execution trace, there does not exist a progress violation.

However, under certain scenarios, such as for a heavily congested bridge, there exists a violation of progress.

So, we need some mechanism to model "heavily congested bridge"
--- prioritize car entry over car exit
--- need some mechanism for prioritizing outgoing actions from a state.



## Progress - action priority

Action priority expressions describe scheduling properties:

High Priority ("<<")

**C = (P||Q)<<{a1,…,an}** specifies a composition in which the actions **a1,..,an** have higher priority than any other action in the alphabet of **P||Q** including the silent action **tau**. *In any choice in this system which has one or more of the actions **a1,..,an** labeling a transition, the transitions labeled with lower priority actions are **discarded**.*

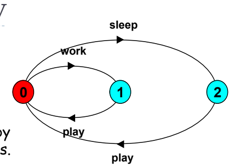
Low Priority (">>")

**C = (P||Q)>>{a1,…,an}** specifies a composition in which the actions **a1,..,an** have lower priority than any other action in the alphabet of **P||Q** including the silent action **tau**. *In any choice in this system which has one or more transitions not labeled by **a1,..,an**, the transitions labeled by **a1,..,an** are **discarded**.*



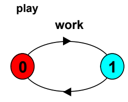
## Progress - action priority

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

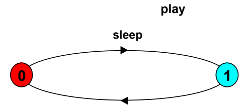



Action priority simplifies the resulting LTS by discarding lower priority actions from choices.

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




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






## 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.

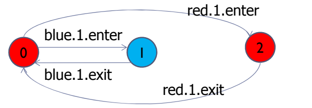
Instead we merely encourage congestion by *lowering the priority of the exit actions of both cars from the bridge.*

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

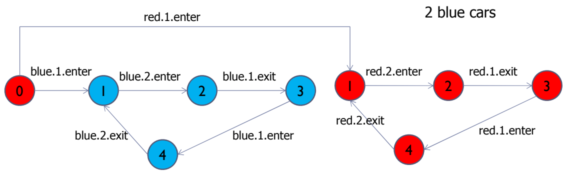
***Progress Analysis ? LTS?***

## Congested bridge model

1 red car
1 blue car




2 red cars
2 blue cars






## 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}**

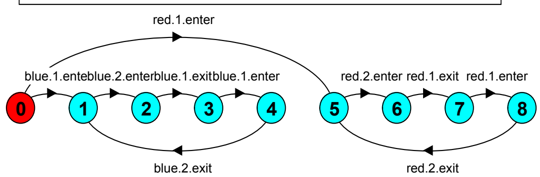
**Progress violation: REDCROSS**
**Path to terminal set of states:**
**blue.1.enter**
**blue.2.enter**
**Actions in terminal set:**
**{blue.1.enter, blue.1.exit, blue.2.enter, blue.2.exit, blue.3.enter, blue.3.exit}**

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.



## 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?***



## 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 - 2 nd revision of single lane bridge model

➡ *Analysis ?*

```
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]
 ).
```



## 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();
  }
}
```

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



## Results from 2nd Revision of Bridge

- No deadlocks.
- Progress requirements met in presence of congestion
  - Both red and blue cars waiting to enter the single lane bridge.



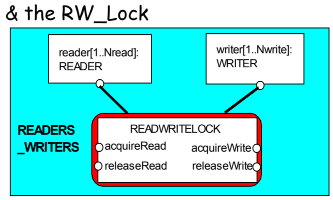
## 7.5 Readers and Writers

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.



## 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).



## 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 are known to the process.

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



## 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.



## 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).
```

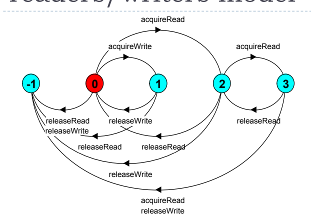
We can check that RW_LOCK satisfies the safety property……

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

➡ ***Safety Analysis ?  LTS?***



## 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 ?***



## 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..Nwrite].releaseWrite}.
```

➡ ***Progress Analysis ?  LTS?***



## RECAP: Progress - action priority

Action priority expressions describe scheduling properties:

High Priority ("<<")

**C = (P||Q)<<{a1,…,an}** specifies a composition in which the actions **a1,..,an** have higher priority than any other action in the alphabet of **P||Q** including the silent action **tau**. *In any choice in this system which has one or more of the actions **a1,..,an** labeling a transition, the transitions labeled with lower priority actions are **discarded**.*

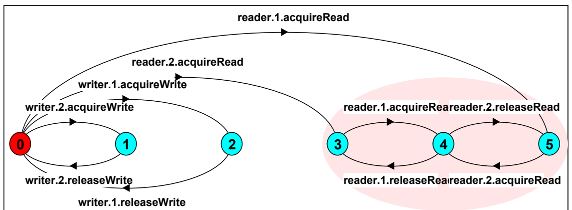
Low Priority (">>")

**C = (P||Q)>>{a1,…,an}** specifies a composition in which the actions **a1,..,an** have lower priority than any other action in the alphabet of **P||Q** including the silent action **tau**. *In any choice in this system which has one or more transitions not labeled by **a1,..,an**, the transitions labeled by **a1,..,an** are **discarded**.*

## 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.






## Progress violation detected

- When release actions have low priority
  - Readers/writers are always hungry
- What is the exact scenario
  - Readers access database and # of readers remains non-zero
  - Writers are starved out
- Do we have a progress violation where readers starve?
  - No, under fair choice!!
    - Either reader or writer accesses database (state 0 in previous slide)
    - If writer chosen, it must release after it acquires, and we come back to state 0.
    - Readers cannot be permanently starved out at state 0, if we have fair choice for outgoing actions.



## 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.**



## 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 to a single writer *when there are no more readers.*



## 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

```java
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) notifyAll();
  }
```

May also be readers waiting



## readers/writers implementation - ReadWritePriority

```java
synchronized public void acquireWrite()
                 throws InterruptedException {
    ++waitingW;
    while (readers>0 || writing) wait();
    --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.*



## 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 system model*
- Practice
  - threads and monitors

Aim: property satisfaction



## Follow-up questions

Abhik Roychoudhury

## 1. Question from post-it note

- Why do we need properties if existing modeling techniques (those taught previously) can guarantee mutual exclusion



## Answer

Mutual exclusion is only one class of safety property.
Deadlock is another popular class of safety properties.
Safety properties are a general class of properties which state that certain "bad" events should never happen in the concurrent system being designed. Now, what is bad, and what is good - depends on the application in question.
The no-deadlock property is a special kind of safety property which is always "bad" - irrespective of the application.

However, we have already seen simple examples where a property p may be a desired safety property in one application, but it may not need to be enforced in another application.



## Answer

Consider the property --- no two processes should be accessing a shared data object. This property is true for applications where access to the critical section is controlled via a binary semaphore. However, for the readers-writers example that we discussed in class, it is possible for several reader processes to be accessing the shared database. Our expectation here is weaker -- we only demand the property that whenever a writer process is accessing the database, no other process (reader or write) is accessing it.



## 2. Question asked during lecture break

For the Promela modeling language is it possible for a condition to be put anywhere in the program?

Answer:

The answer is yes. Promela allows for the program to have statements like

x > 0; y > 0; z > 0;

So, when the control reaches the statement x > 0 -- the execution will check whether x is greater than 0. If x is greater than 0, the execution of this condition behaves like a skip statement. If x is not greater than 0, the execution will be blocked (this may be unblocked by another process modifying the value of x, if x is a shared variable).



## 3. Another question asked

- You discussed about starvation properties today. What if the scheduler for my concurrent program introduces starvation?



## Answer

Once again, we must ensure that we do not confuse the levels of abstraction.

A concurrent program is running with the help of an underlying scheduler.

When we reason about progress/no-starvation properties the concurrent program, we are assuming an underlying "fair" scheduler - at least fair to the extent that it does not ignore one of the program threads forever. Now, exactly how this "fairness" is implemented - that is upto to the systems software writer who will write the scheduler. As an application programmer, you want to be sure that your program will not run into starvation scenarios even when the scheduler is guaranteed to have "fair choice".