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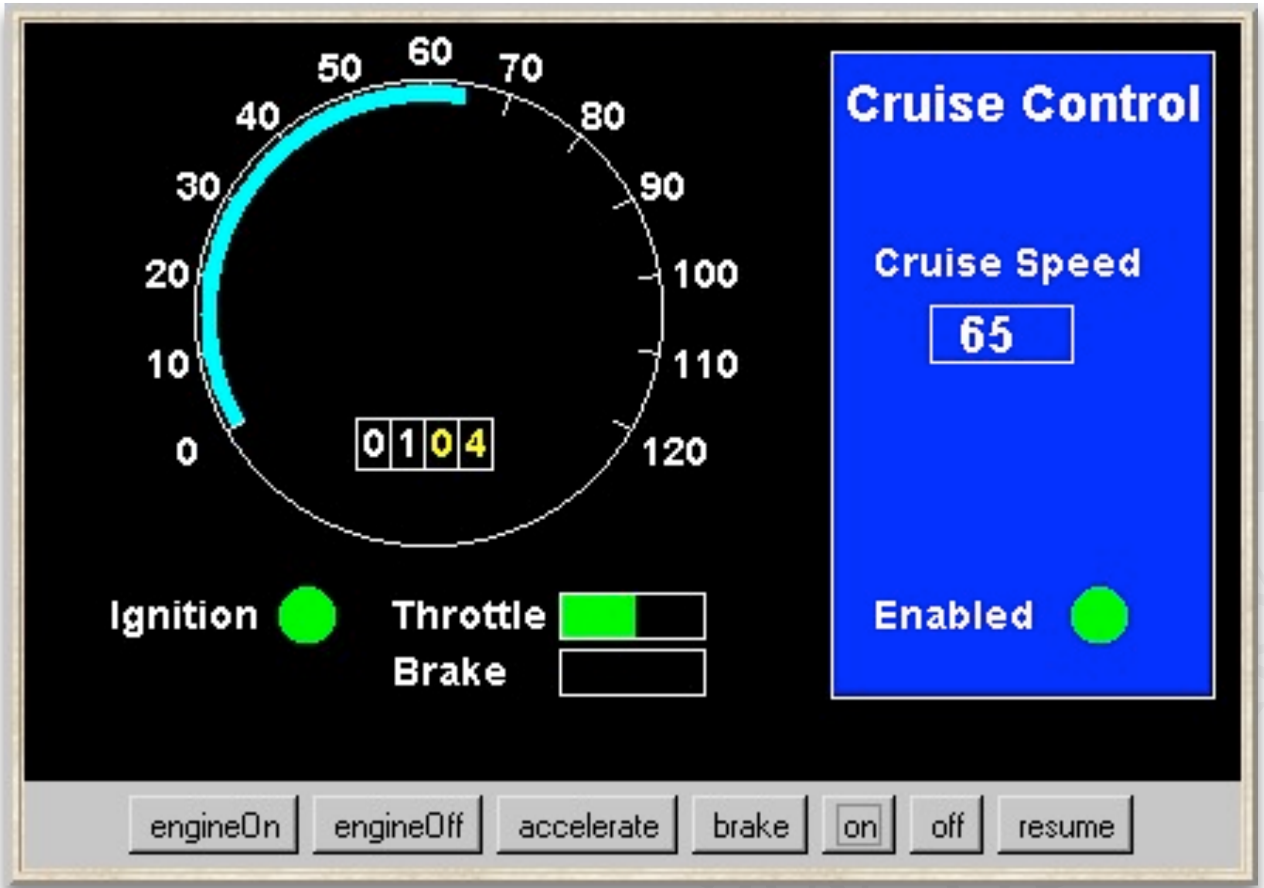
Dynamic Systems

Repetition: Chapter 8
Model-Based Design

Requirements

Model

Java



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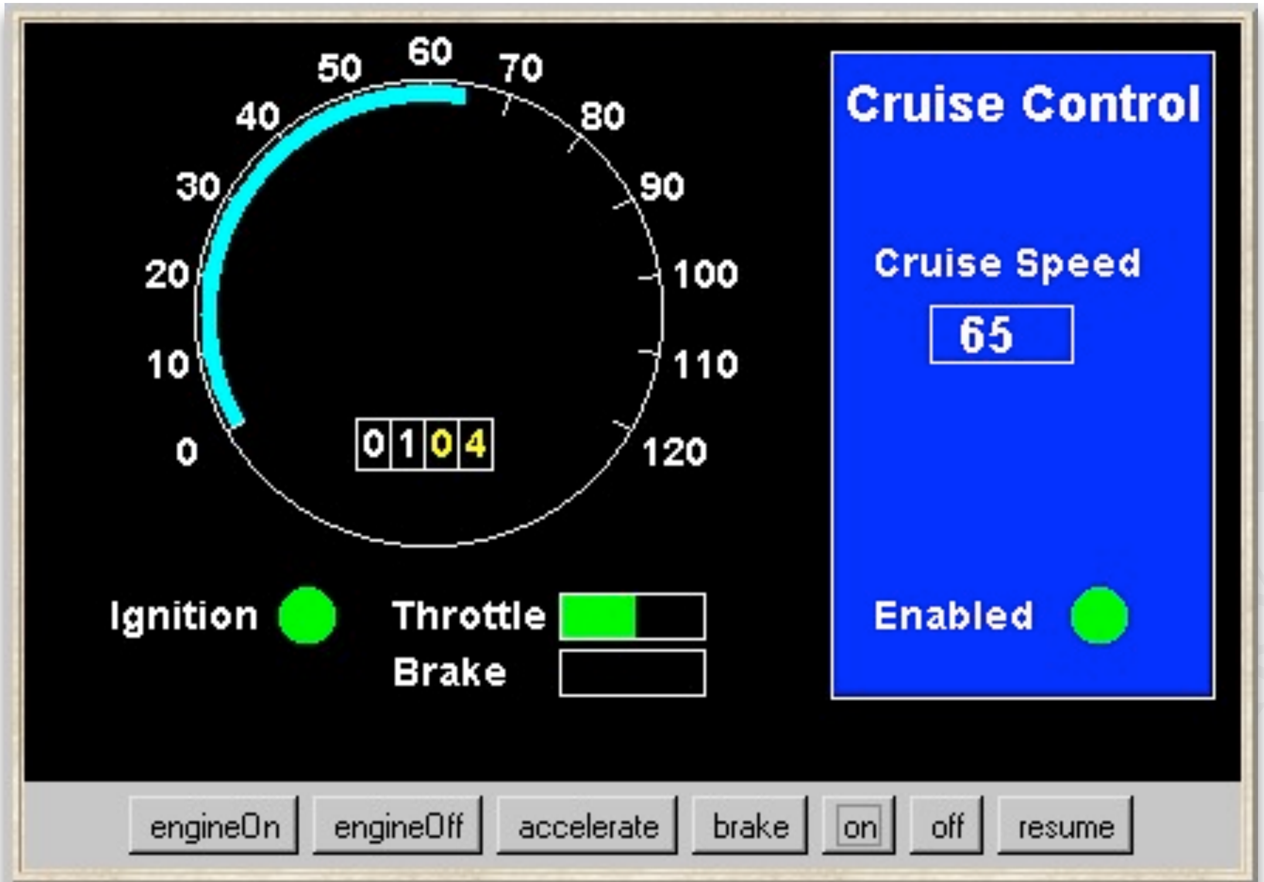
Repetition: Chapter 8 Model-Based Design

Requirements

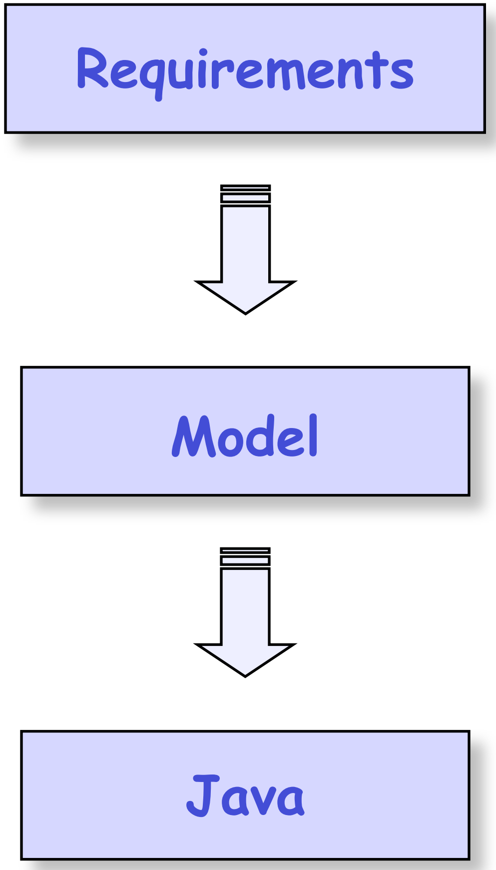
↓

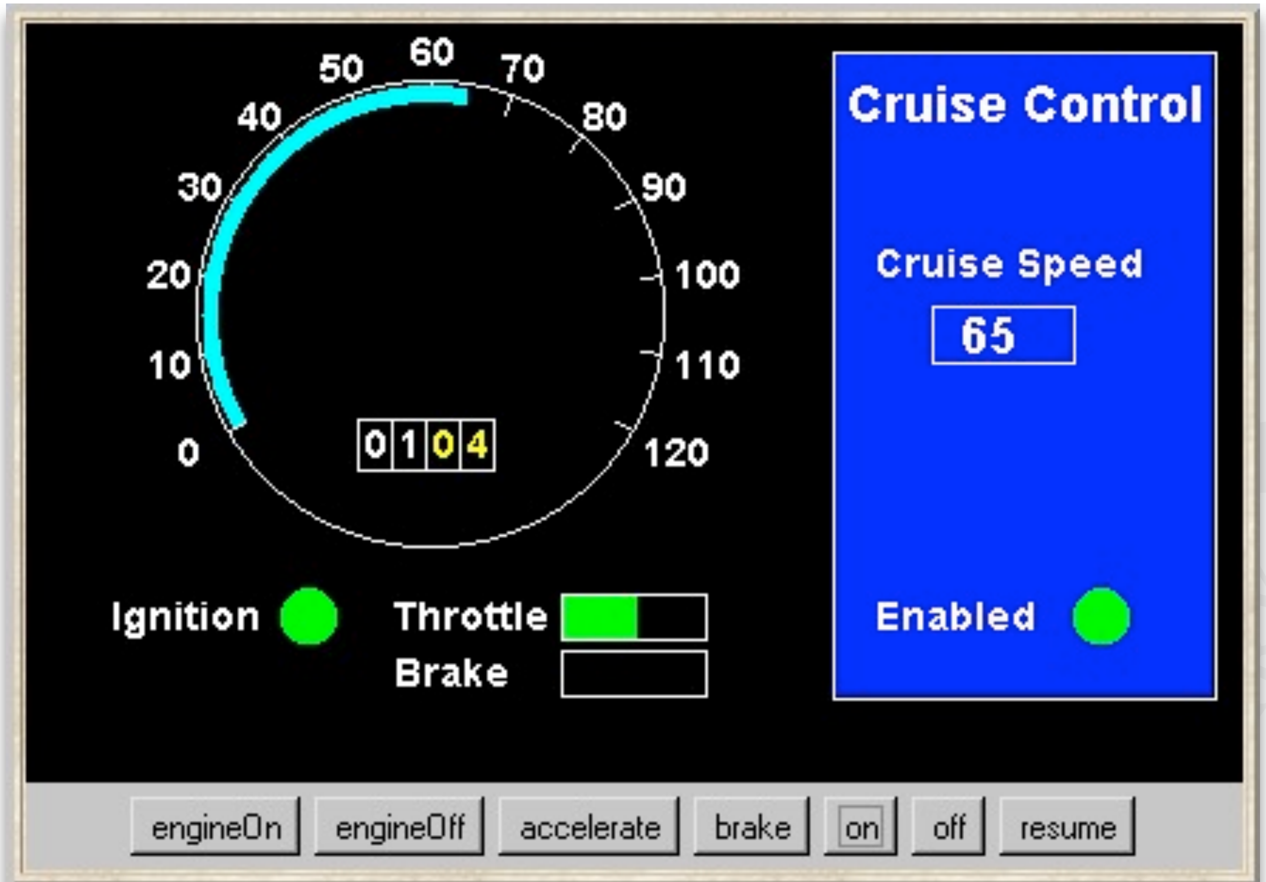
Model

Java



Repetition: Chapter 8
Model-Based Design





Course Outline

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2. Processes and Threads
3. Concurrent Execution
4. Shared Objects & Interference
5. Monitors & Condition Synchronization
6. Deadlock
7. Safety and Liveness Properties
8. Model-based Design

The main basic
Concepts
Models
Practice

Advanced topics …

9. Dynamic systems
10. Message Passing
11. Concurrent Software Architectures
12. Timed Systems
13. Program Verification
14. Logical Properties

Dynamic Systems

Dynamic Systems

Concepts: **dynamic** creation and deletion of **processes**

Resource allocation example – varying number of users and resources.

master-slave interaction

Dynamic Systems

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Models: static - fixed populations with cyclic behavior

interaction

Dynamic Systems

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Concepts: **dynamic** creation and deletion of **processes**

Resource allocation example – varying number of users and resources.

master-slave interaction

Models: **static - fixed populations with cyclic behavior**

interaction

Practice: **dynamic** creation and deletion of **threads**

(# active threads varies during execution)

Resource allocation algorithms

Java join() method

9.1 Golf Club Program

Players at a Golf Club hire golf balls and then return them after use.

Player d4 is waiting for four balls

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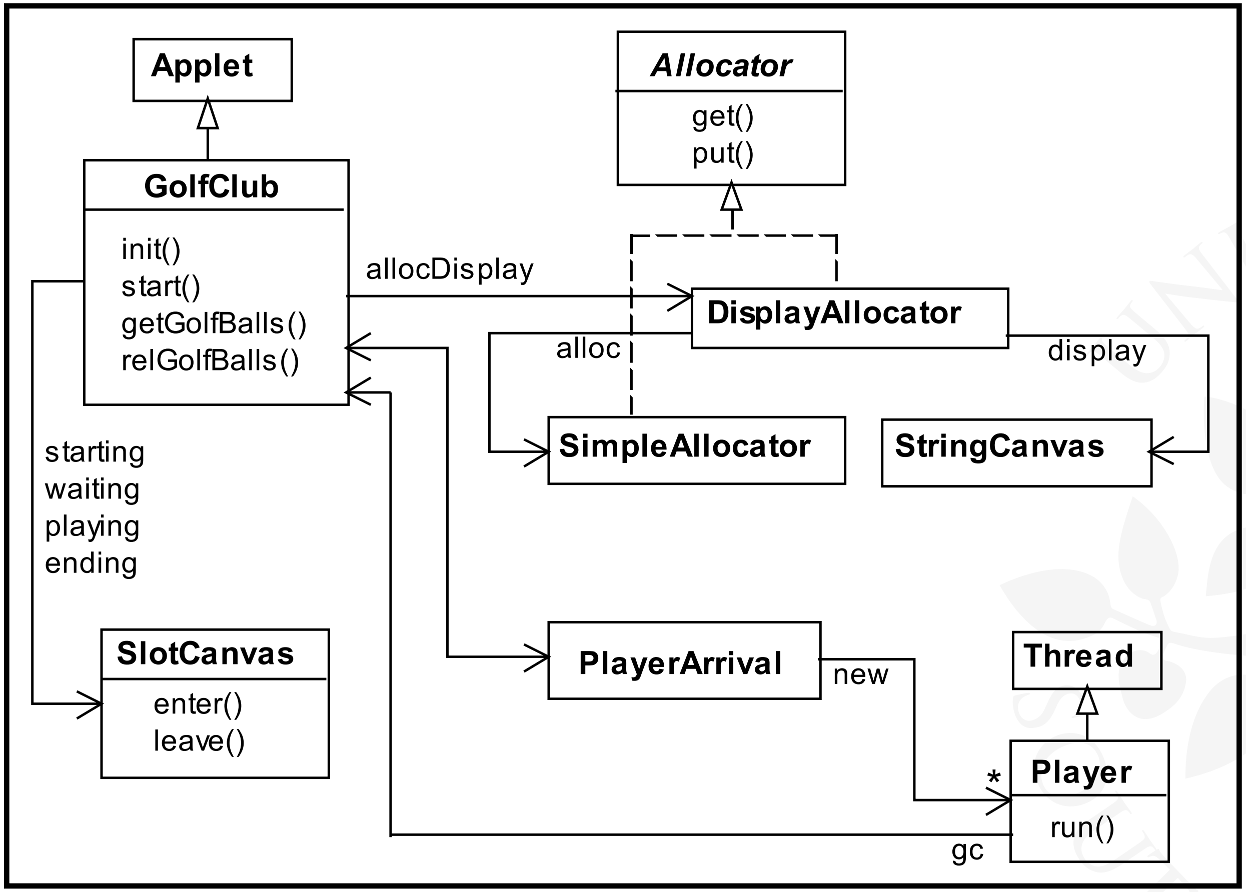
Players at a Golf Club hire golf balls and then return them after use.

Player d4 is waiting for four balls

Expert players tend not to lose any golf balls and only hire one or two. **Novice** players hire more balls, so that they have spares during the game in case of loss. However, they buy replacements for lost balls so that they return the same number that they originally hired.

Golf Club - Java Implementation



Golf Club - Java Implementation

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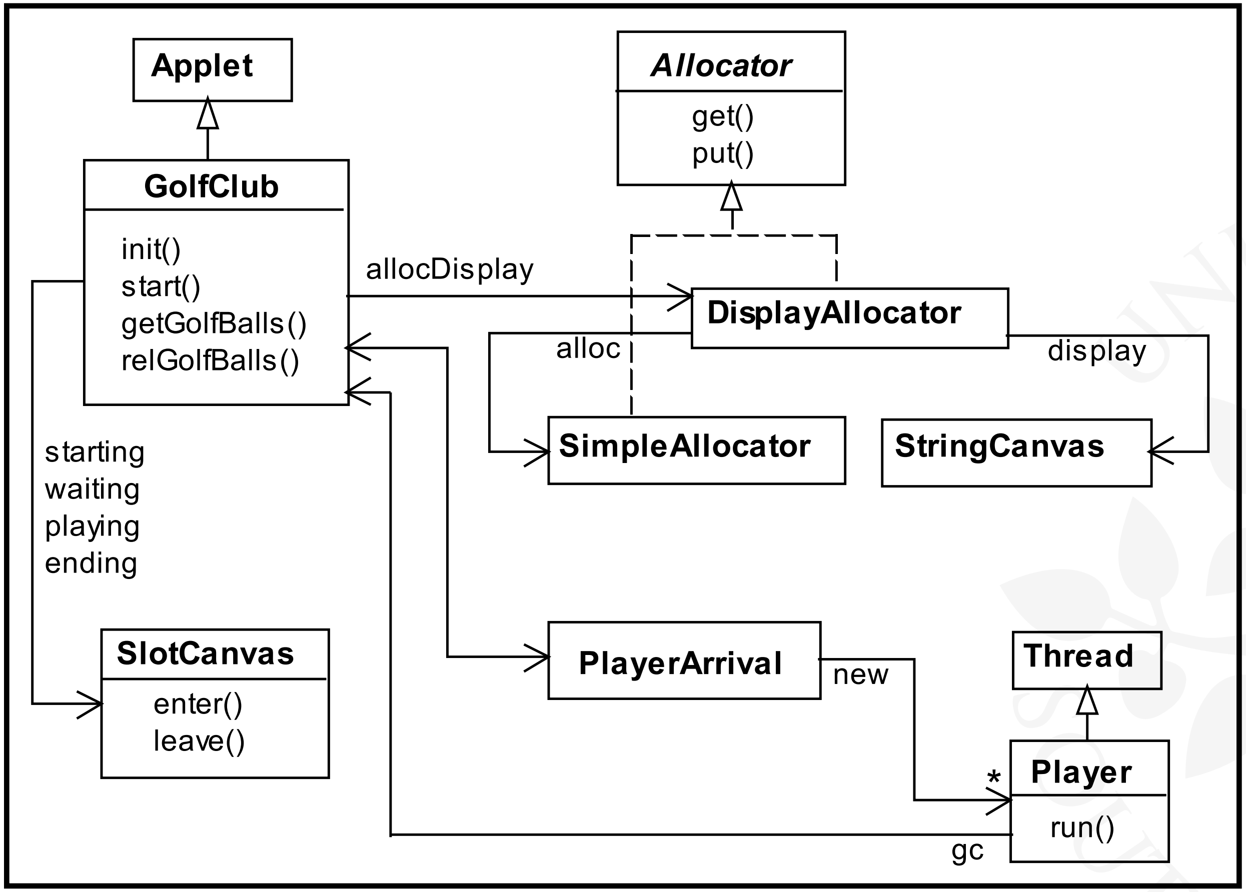

The Java interface **Allocator** permits us to develop a few implementations of the golf ball allocator without modifying the rest of the program.

```java
public interface Allocator {
  public void get(int n) throws InterruptedException;
  public void put(int n);
}
```

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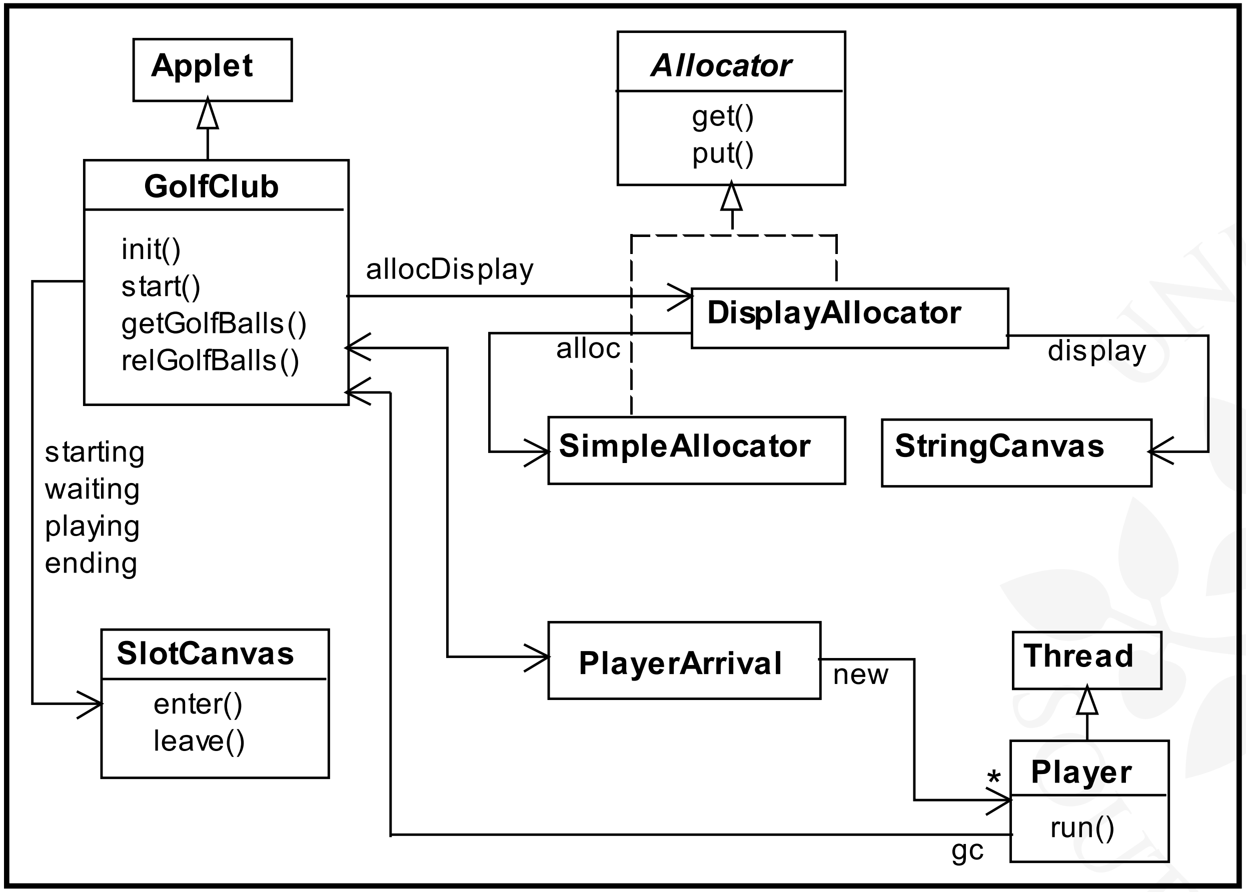

The Java interface **Allocator** permits us to develop a few implementations of the golf ball allocator without modifying the rest of the program.

DisplayAllocator class implements this interface and delegates calls to **get** and **put** to **SimpleAllocator**.

```java
public interface Allocator {
  public void get(int n) throws InterruptedException;
  public void put(int n);
}
```

Java Implementation - SimpleAllocator Monitor

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```
public class SimpleAllocator implements Allocator {
  private int available;

  public SimpleAllocator(int n)
    { available = n; }
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    available -= n;
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get blocks a calling thread until sufficient golf balls are available.

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    available += n;
    notifyAll();
  }
}
```

get blocks a calling thread until sufficient golf balls are available.

A novice thread requesting a large number of balls may be overtaken and remain blocked!

Java Implementation - Player Thread

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```
class Player extends Thread {
  private GolfClub gc;
  private String name;
  private int nballs;

  Player(GolfClub g, int n, String s) {
     gc = g; name = s; nballs =n;
  }

  public void run() {
    try {
      gc.getGolfBalls(nballs,name);
      Thread.sleep(gc.playTime);
      gc.relGolfBalls(nballs,name);
    } catch (InterruptedException e){}
  }
}
```

Java Implementation - Player Thread


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  Player(GolfClub g, int n, String s) {
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    } catch (InterruptedException e){}
  }
}
```

The *run()* method terminates after releasing golf balls. New player threads are created dynamically.

Dynamic Systems In Java

Dynamic Systems In Java

Approach 1: explicitly create threads,

- Create one thread for each player

```
new Thread(new Player(...)).start()
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Dynamic Systems In Java

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```

- Drawbacks:
  - thread life cycle overhead
  - resources consumption, especially memory
  - Stability: no controlled limits on #threads that can be created, OutOfMemoryError

Dynamic Systems In Java

Approach 2: Executor framework

```
interface Executor{
   void execute(Runnable command);
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Dynamic Systems In Java

Approach 2: Executor framework

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interface Executor{
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Executor exec = Executors.newFixedThreadPool(NTHREADS);
exec.execute(new Player(...));
```

Dynamic Systems In Java

Approach 2: Executor framework

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interface Executor{
    void execute(Runnable command);
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```
Executor exec = Executors.newFixedThreadPool(NTHREADS);
exec.execute(new Player(...));
```

- By decoupling the task submission from execution, we can easily change or specify execution policies, such as
  - execution order, how many tasks are allowed to run concurrently and how many are queued, etc.

9.2 Golf Club Model

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Allocator:

```
const N=5        // maximum #golf balls
range B=0..N     // available range

ALLOCATOR = BALL[N],
BALL[b:B] = (when (b>0) get[i:1..b]->BALL[b-i]
            |put[j:1..N]           ->BALL[b+j]
            ).
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Allocator will accept requests for up to b balls, and block requests for more than b balls.

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How do we model the potentially infinite stream of dynamically created player threads?

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How do we model the potentially infinite stream of dynamically created player threads?

Cannot model infinite state spaces, but can model infinite (repetitive) behaviors.

Golf Club Model

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Players:

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```
range R=1..N   //request range
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Golf Club Model

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Fixed population of golfers: infinite stream of requests.

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Golf Club Model

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set Experts = {alice,bob,chris}
set Novices = {dave,eve}
set Players = {Experts,Novices}
```

Fixed population of golfers: infinite stream of requests.

Golf Club Model

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Players is the union of Experts and Novices.

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set Players = {Experts,Novices}

HANDICAP =
  ({Novices.{need[3..N]},Experts.need[1..2]}
           -> HANDICAP
  ) +{Players.need[R]}.
```

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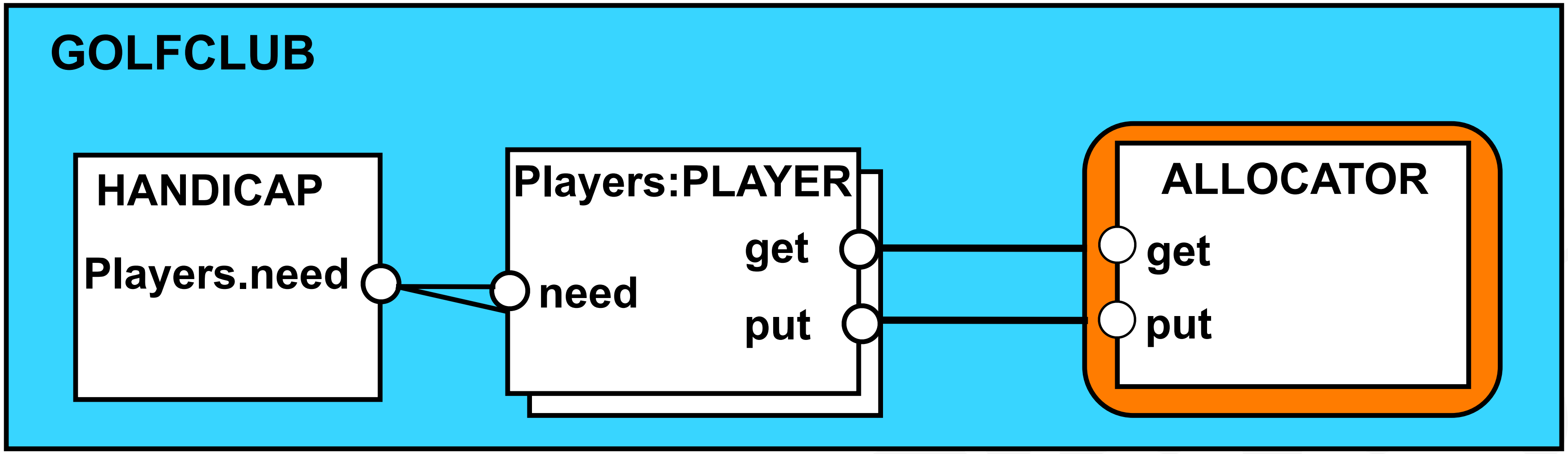
Fixed population of golfers: infinite stream of requests.

Players is the union of Experts and Novices.

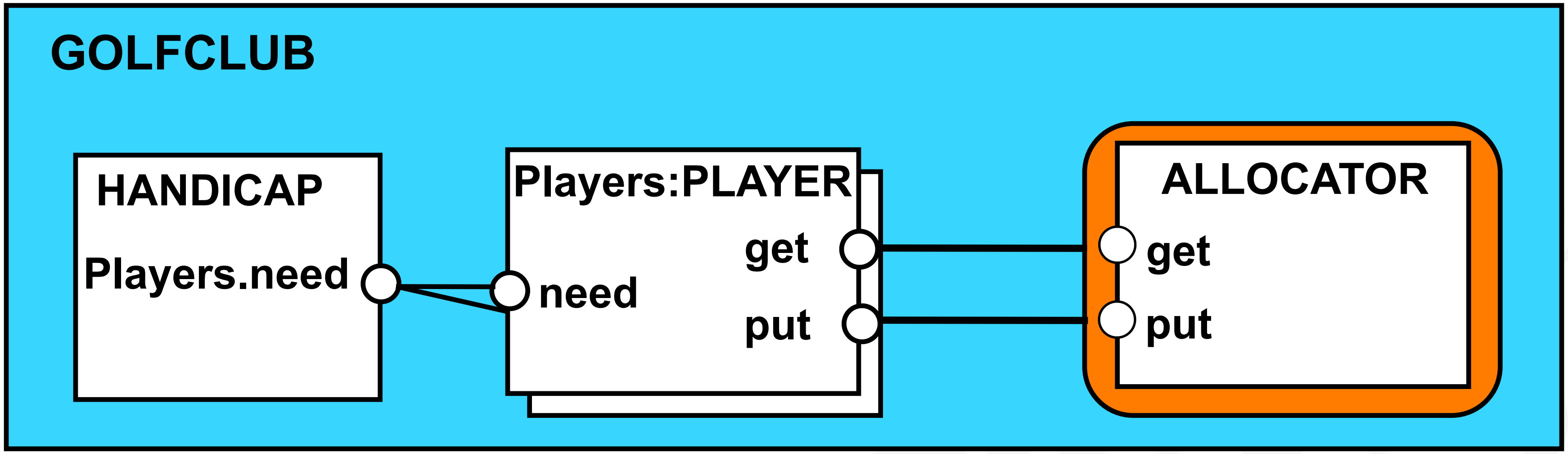
Constraint on need action of each player.

Golf Club Model - Analysis




```
||GOLFCLUB =( Players:PLAYER
             ||Players::ALLOCATOR
             ||HANDICAP).
```

Golf Club Model - Analysis




```
||GOLFCLUB =( Players:PLAYER
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```

Safety? Do players return the right number of balls?

Liveness? Are players eventually allocated balls ?

Golf Club Model - Liveness


```
progress NOVICE = {Novices.get[R]}
progress EXPERT = {Experts.get[R]}
||ProgressCheck = GOLFCLUB >>{Players.put[R]}.
```

Golf Club Model - Liveness

```
progress NOVICE = {Novices.get[R]}
progress EXPERT = {Experts.get[R]}
||ProgressCheck = GOLFCLUB >>{Players.put[R]}.
```

```
Progress violation: NOVICE
Trace to terminal set of states:
     alice.need.2
     bob.need.2
     chris.need.2
     chris.get.2
     dave.need.5
     eve.need.5
Cycle in terminal set:
     alice.get.2
     alice.put.2
Actions in terminal set:
     {alice, bob, chris}.{get, put}[2]
```

Golf Club Model - Liveness


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Cycle in terminal set:
     alice.get.2
     alice.put.2
Actions in terminal set:
     {alice, bob, chris}.{get, put}[2]
```

Novice players dave and eve suffer starvation. They are continually overtaken by experts alice, bob and chris.

9.3 Fair Allocation

Allocation in arrival order, using tickets:

```
const TM = 5        // maximum ticket
range T  = 1..TM    // ticket values

TICKET     = NEXT[1],
NEXT[t:T] = (ticket[t]->NEXT[t%TM+1]).
```

9.3 Fair Allocation

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Players and Allocator:

```
PLAYER      = (need[b:R]->PLAYER[b]),
PLAYER[b:R]= (ticket[t:T]->get[b][t]->put[b]
              ->PLAYER[b]).

ALLOCATOR        = BALL[N][1],
BALL[b:B][t:T]  =
  (when (b>0) get[i:1..b][t]->BALL[b-i][t%TM+1]
  |put[j:1..N]              ->BALL[b+j][t]
  ).
```

Fair Allocation - Analysis

Ticketing increases the size of the model for analysis. We compensate by modifying the HANDICAP constraint:

```
HANDICAP =
  ({Novices.{need[4]},Experts.need[1]}-> HANDICAP
  ) +{Players.need[R]}.
```

Experts use 1 ball,
Novices use 4 balls.

```
||GOLFCLUB =( Players:PLAYER
            ||Players::(ALLOCATOR||TICKET)
            ||HANDICAP).
```

Fair Allocation - Analysis

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||GOLFCLUB =( Players:PLAYER
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Safety?

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9.4 Revised Golf Club Program - FairAllocator Monitor

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```
public class FairAllocator implements Allocator {
  private  int available;
  private  long turn = 0; // next ticket to be dispensed
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 public FairAllocator(int n) { available = n; }
```

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Block calling thread until sufficient balls and next turn.

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  synchronized public void get(int n)
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    long myturn = turn;  ++turn;
    while (n>available || myturn != next) wait();
    ++next; available -= n;
    notifyAll();
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```

Block calling thread until sufficient balls and next turn.

Why is it necessary for get to include notifyAll()?

Revised Golf Club Program - FairAllocator

Revised Golf Club Program - FairAllocator

Players **g1** and **h1** are waiting. Even though two balls are available, they cannot overtake player **f4.**

Revised Golf Club Program - FairAllocator

Players **g1** and **h1** are waiting. Even though two balls are available, they cannot overtake player **f4.**

What happens if **c**, **d** and **e** all return their golf balls?

9.5 Bounded Allocation

Allocation in arrival order is not efficient. A bounded allocation scheme allows experts to overtake novices but denies starvation by setting an upper bound on the number of times a novice can be overtaken.

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9.5 Bounded Allocation

Allocation in arrival order is not efficient. A bounded allocation scheme allows experts to overtake novices but denies starvation by setting an upper bound on the number of times a novice can be overtaken.

We model players who have overtaken others as a set.

```
const False = 0
const True  = 1
range Bool  = 0..1

ELEMENT(Id=0)  = IN[False],
IN[b:Bool]  = ( add[Id]            -> IN[True]
              | remove[Id]         -> IN[False]
              | contains[Id][b] -> IN[b]
              ).
||SET = (forall[i:T] (ELEMENT(i))).
```

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```

A SET is modeled as the parallel composition of elements

Bounded Allocation - Allocator Model

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We model bounded overtaking using tickets, where ticket numbers indicate the order in which players make their requests. The allocator records which ticket number is `next`.

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Overtaking occurs when we allocate balls to a player whose `turn` - indicated by his/her ticket number - is subsequent to a waiting player with the `next` ticket. The overtaking player is added to the overtaking set, and a count `ot` is incremented to indicate the number of times `next` has been overtaken.

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Overtaking occurs when we allocate balls to a player whose `turn` - indicated by his/her ticket number - is subsequent to a waiting player with the `next` ticket. The overtaking player is added to the overtaking set, and a count `ot` is incremented to indicate the number of times `next` has been overtaken.

When the count equals the bound, we allow allocation to the `next` player only. When allocation is made to the `next` player, we update `next` to indicate the next (waiting) player. We skip the ticket numbers of overtaking players who already received their allocation, remove each of these intervening players from the overtaking set and decrement the overtaking count `ot` accordingly. (This is achieved in the local process, `WHILE`, in the ALLOCATOR model.)

Bounded Allocation - Allocator Model

Bounded Allocation - Allocator Model

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```
ALLOCATOR   = BALL[N][1][0],    //initially N balls, 1 is next, empty set
BALL[b:B][next:T][ot:0..Bd] =
```

Bounded Allocation - Allocator Model

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BALL[b:B][next:T][ot:0..Bd] =
     (when (b>0 && ot<Bd) get[i:1..b][turn:T] ->
```

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          if (turn!=next) then
               (add[turn] -> BALL[b-i][next][ot+1])
          else
               WHILE[b-i][next%TM+1][ot]
```

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          else
               WHILE[b-i][next%TM+1][ot]
     |when (b>0 && ot==Bd) get[i:1..b][next] ->
               WHILE[b-i][next%TM+1][ot]
```

Bounded Allocation - Allocator Model


```
ALLOCATOR   = BALL[N][1][0],    //initially N balls, 1 is next, empty set
BALL[b:B][next:T][ot:0..Bd] =
      (when (b>0 && ot<Bd) get[i:1..b][turn:T] ->
            if (turn!=next) then
                  (add[turn] -> BALL[b-i][next][ot+1])
            else
                  WHILE[b-i][next%TM+1][ot]
      |when (b>0 && ot==Bd) get[i:1..b][next] ->
                  WHILE[b-i][next%TM+1][ot]
      |put[j:1..N] -> BALL[b+j][next][ot]
),
```

Bounded Allocation - Allocator Model

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```
ALLOCATOR   = BALL[N][1][0],    //initially N balls, 1 is next, empty set
BALL[b:B][next:T][ot:0..Bd] =
      (when (b>0 && ot<Bd) get[i:1..b][turn:T] ->
            if (turn!=next) then
                  (add[turn] -> BALL[b-i][next][ot+1])
            else
                  WHILE[b-i][next%TM+1][ot]
      |when (b>0 && ot==Bd) get[i:1..b][next] ->
                  WHILE[b-i][next%TM+1][ot]
      |put[j:1..N] -> BALL[b+j][next][ot]
),
WHILE[b:B][next:T][ot:0..Bd] =
      (contains[next][yes:Bool] ->
```

Bounded Allocation - Allocator Model


```
ALLOCATOR  = BALL[N][1][0],    //initially N balls, 1 is next, empty set
BALL[b:B][next:T][ot:0..Bd] =
     (when (b>0 && ot<Bd) get[i:1..b][turn:T] ->
          if (turn!=next) then
               (add[turn] -> BALL[b-i][next][ot+1])
          else
               WHILE[b-i][next%TM+1][ot]
     |when (b>0 && ot==Bd) get[i:1..b][next] ->
               WHILE[b-i][next%TM+1][ot]
     |put[j:1..N] -> BALL[b+j][next][ot]
),
WHILE[b:B][next:T][ot:0..Bd] =
     (contains[next][yes:Bool] ->
          if (yes) then
            (remove[next] -> WHILE[b][next%TM+1][ot-1])
          else BALL[b][next][ot]
).
```

Bounded Allocation - Allocator Model

where

```
const N  =  5      // maximum #golf balls
const Bd =  2      // bound on overtaking
range B  =  0..N   // available range

const TM = N + Bd  // maximum ticket
range T  = 1..TM   // ticket values
```

Bounded Allocation - Allocator Model

where

```
const N  =  5      // maximum #golf balls
const Bd =  2      // bound on overtaking
range B  =  0..N   // available range

const TM = N + Bd // maximum ticket
range T  = 1..TM  // ticket values
```

```
||GOLFCLUB = (Players:PLAYER
             || ALLOCATOR || TICKET || SET
             || HANDICAP
             )/ {Players.get/get, Players.put/put,
                 Players.ticket/ticket}.
```

Bounded Allocation - An Explanatory Trace

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```
eve.need.4          Experts Eve and Dave
dave.need.4
chris.need.1        Novices Alice, Bob and Chris
alice.need.1
bob.need.1
alice.ticket.1
alice.get.1.1       Alice gets 1 ball, ticket 1
contains.2.0        Ticket 2 is next
bob.ticket.2
bob.get.1.2         Two allocated, three available
contains.3.0        Ticket 3 is next
dave.ticket.3       Dave needs four balls: waits
chris.ticket.4
chris.get.1.4       Chris overtakes
add.4
eve.ticket.5        Eve needs four balls: waits
alice.put.1
alice.ticket.6
alice.get.1.6       Alice overtakes
add.6
bob.put.1
bob.ticket.7
bob.get.1.7         Bob overtakes: bound reached
add.7
```

Using animation, we can perform a scenario and produce a trace.

Bounded Allocation - An Explanatory Trace


```
chris.put.1
chris.ticket.8      Chris waits: three available
alice.put.1
alice.ticket.1      Alice waits: four available
dave.get.4.3        Dave gets four balls
contains.4.1        remove intervening overtaker
remove.4
contains.5.0        Ticket 5 (Eve) is next
dave.put.4
dave.ticket.2
alice.get.1.1       Alice overtakes: bound reached
add.1
bob.put.1
bob.ticket.3
eve.get.4.5         Eve gets four balls
contains.6.1        remove intervening overtakers
remove.6
contains.7.1
remove.7
contains.8.0        Ticket 8 (Chris) is next
. . .
```

Bounded Allocation - An Explanatory Trace


```
chris.put.1
chris.ticket.8     Chris waits: three available
alice.put.1
alice.ticket.1     Alice waits: four available
dave.get.4.3       Dave gets four balls
contains.4.1       remove intervening overtaker
remove.4
contains.5.0       Ticket 5 (Eve) is next
dave.put.4
dave.ticket.2
alice.get.1.1      Alice overtakes: bound reached
add.1
bob.put.1
bob.ticket.3
eve.get.4.5        Eve gets four balls
contains.6.1       remove intervening overtakers
remove.6
contains.7.1
remove.7
contains.8.0       Ticket 8 (Chris) is next
. . .
```

Exhaustive checking:

Safety?

Liveness?

Can we also specify the bounded nature of this allocator as a safety property?

Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

Bounded Allocation – Safety Property

For each player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
```

Bounded Allocation – Safety Property

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For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
```

Action labels used in expressions or as parameter values must be prefixed with a single quote.

Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]  -> WAITING[t][0]
    |[Players].get[R][T]         -> BOUND
    ),
```

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Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]   -> WAITING[t][0]
    |[Players].get[R][T]        -> BOUND
    ),
WAITING[ticket:T][overtaken:0..Bd] =
```

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Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]   -> WAITING[t][0]
    |[Players].get[R][T]         -> BOUND
    ),
WAITING[ticket:T][overtaken:0..Bd] =
    ([P].get[b:R][ticket] -> BOUND
```

Action labels used in expressions or as parameter values must be prefixed with a single quote.

Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]  -> WAITING[t][0]
    |[Players].get[R][T]         -> BOUND
    ),
WAITING[ticket:T][overtaken:0..Bd] =
    ([P].get[b:R][ticket] -> BOUND
    |{Players\{[P]}}.get[b:R][t:T] ->
```

Action labels used in expressions or as parameter values must be prefixed with a single quote.

Bounded Allocation – Safety Property

For **each** player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]  -> WAITING[t][0]
    |[Players].get[R][T]         -> BOUND
    ),
WAITING[ticket:T][overtaken:0..Bd] =
    ([P].get[b:R][ticket] -> BOUND
    |{Players\{[P]}}.get[b:R][t:T] ->
        if (t>ticket)
        then WAITING[ticket][overtaken+1]
        else WAITING[ticket][overtaken]
```

> Action labels used in expressions or as parameter values must be prefixed with a single quote.

Bounded Allocation – Safety Property

For each player, check that he/she is not overtaken more than bound times. Overtaking is indicated by an allocation to another player whose ticket t lies between the turn of the player and the latest ticket.

```
property BOUND(P='alice) =
    ([P].ticket[t:T]  -> WAITING[t][0]
    |[Players].get[R][T]          -> BOUND
    ),
WAITING[ticket:T][overtaken:0..Bd] =
    ([P].get[b:R][ticket] -> BOUND
    |{Players\{[P]}}.get[b:R][t:T] ->
         if (t>ticket)
         then WAITING[ticket][overtaken+1]
         else WAITING[ticket][overtaken]
    |Players.ticket[last:T] ->WAITING[ticket][overtaken]
).
```

Action labels used in expressions or as parameter values must be prefixed with a single quote.

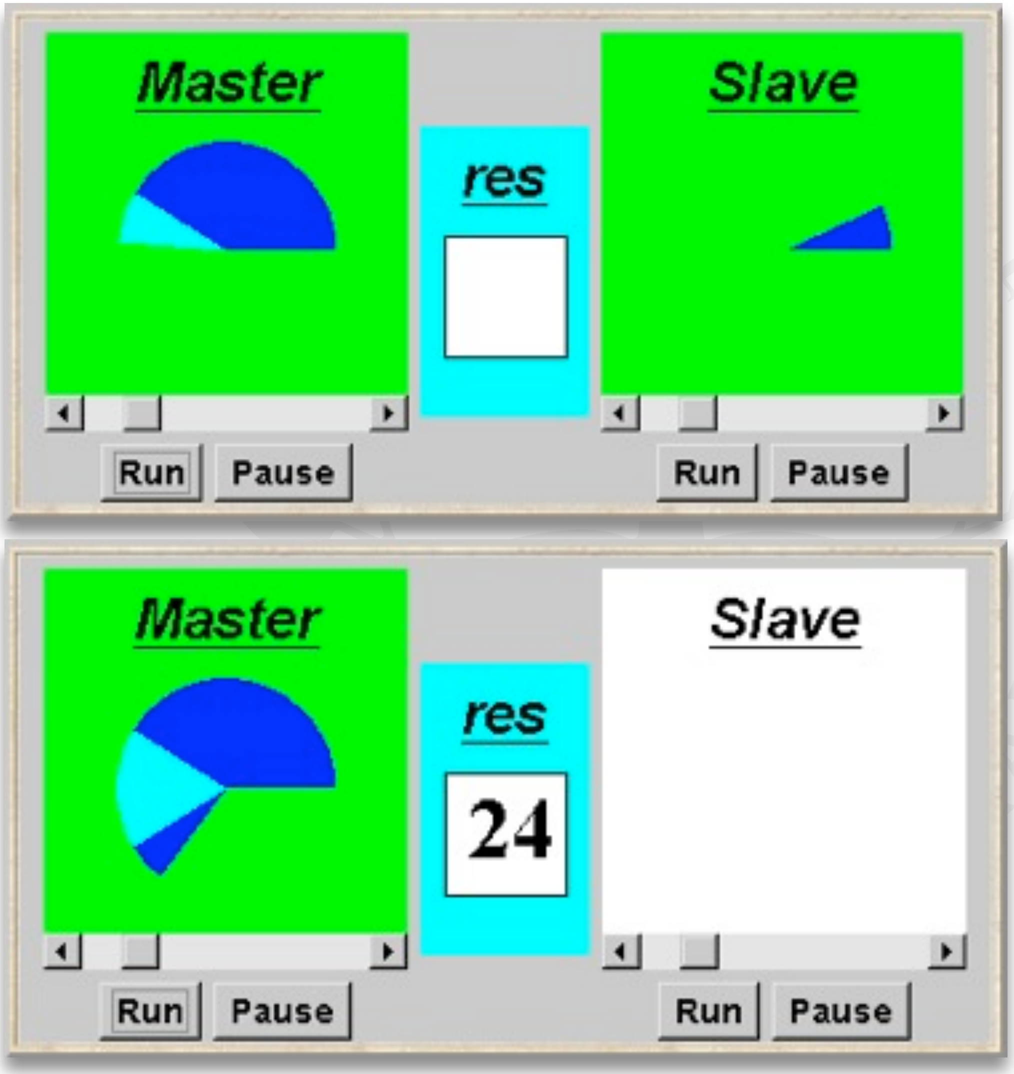
9.6 Bounded Overtaking Allocator - Implementation

Implementation of the **`BoundedOvertakingAllocator`** monitor follows the algorithm in the model.

Implementation of the **BoundedOvertakingAllocator** monitor follows the algorithm in the model.

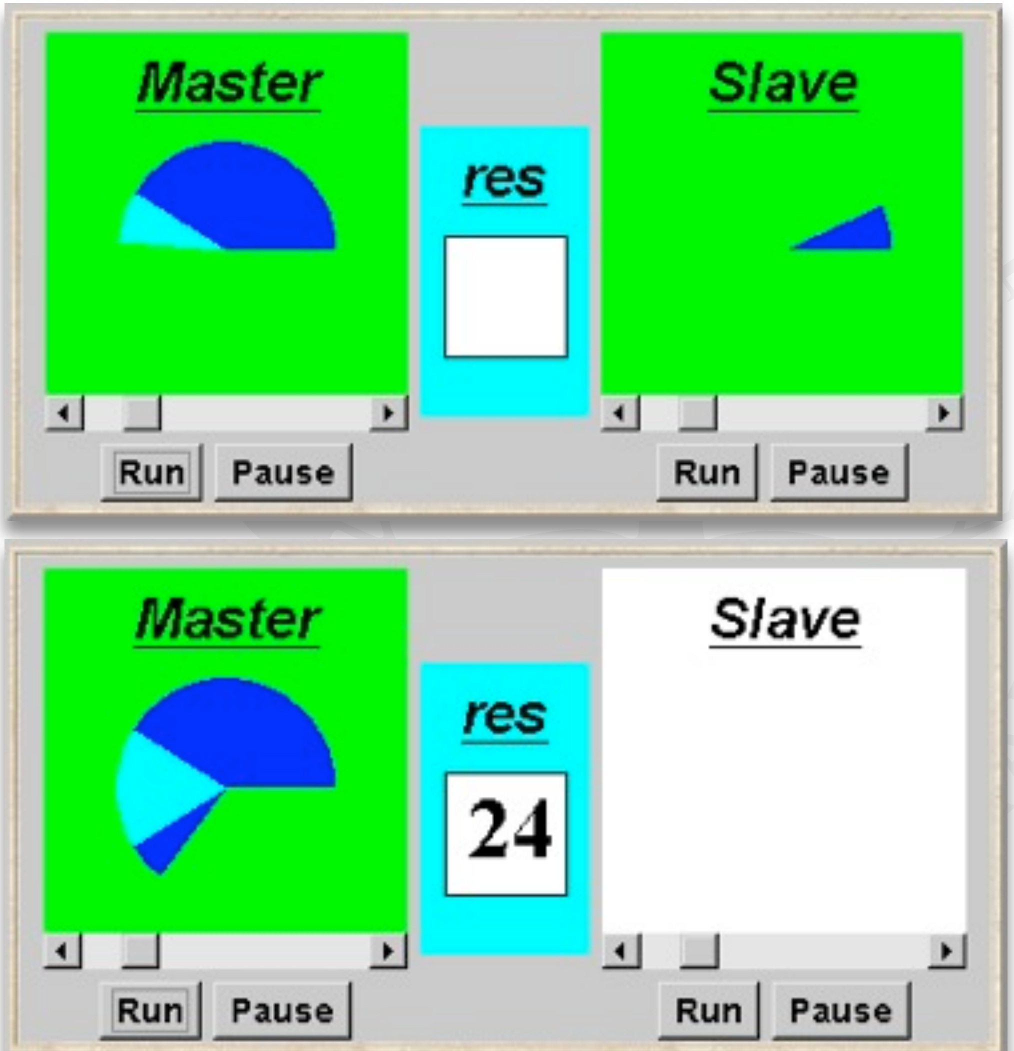
Novice player **f4** has been overtaken by expert players **g1**, **h1** and **i1**. Since the overtaking bound of three has been exceeded, players **j1** and **k1** are blocked although there are two golf balls available.

9.7 Master-Slave Program



9.7 Master-Slave Program

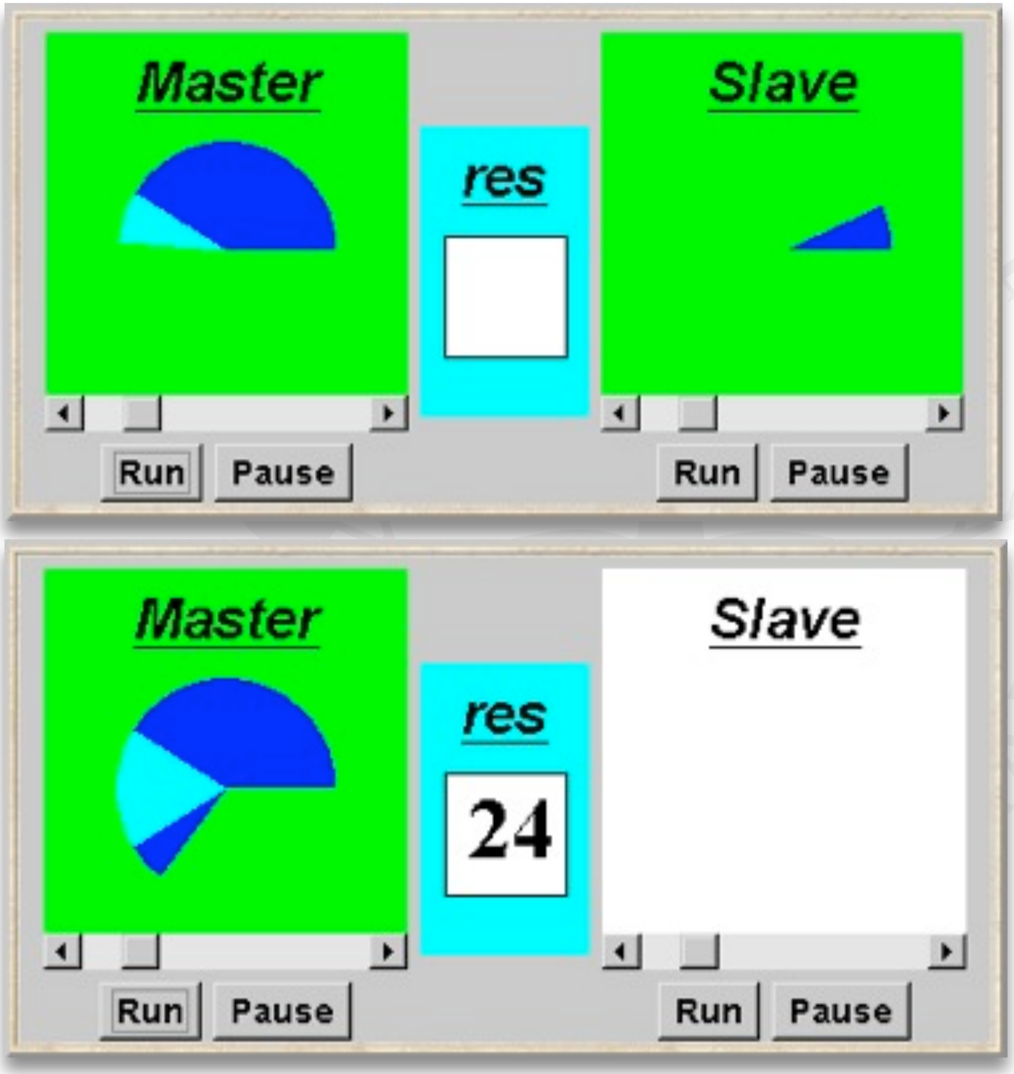
A Master thread creates a Slave thread to perform some task (eg. I/O) and continues.



9.7 Master-Slave Program

A Master thread creates a Slave thread to perform some task (eg. I/O) and continues.

Later, the Master synchronizes with the Slave to collect the result.

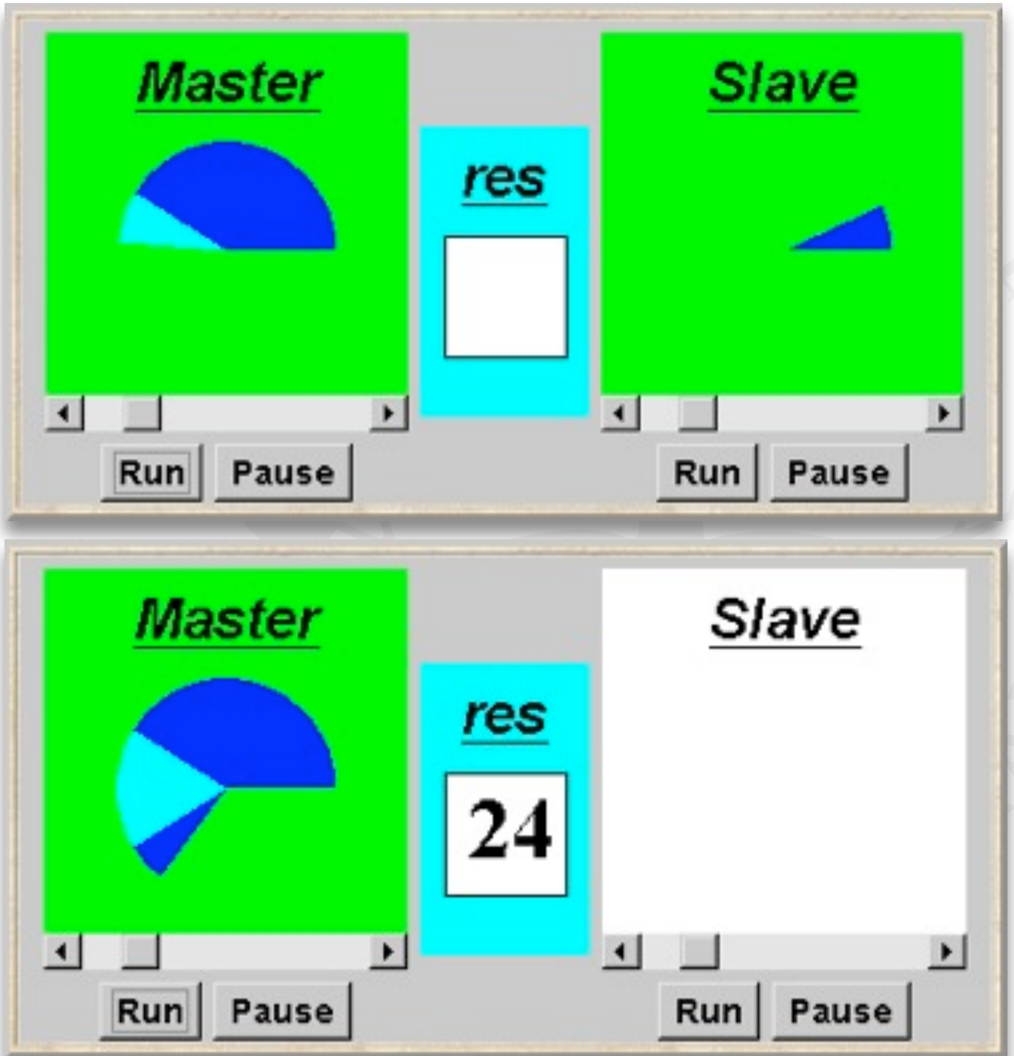


9.7 Master-Slave Program

A Master thread creates a Slave thread to perform some task (eg. I/O) and continues.

Later, the Master synchronizes with the Slave to collect the result.

How can we avoid busy waiting for the Master?



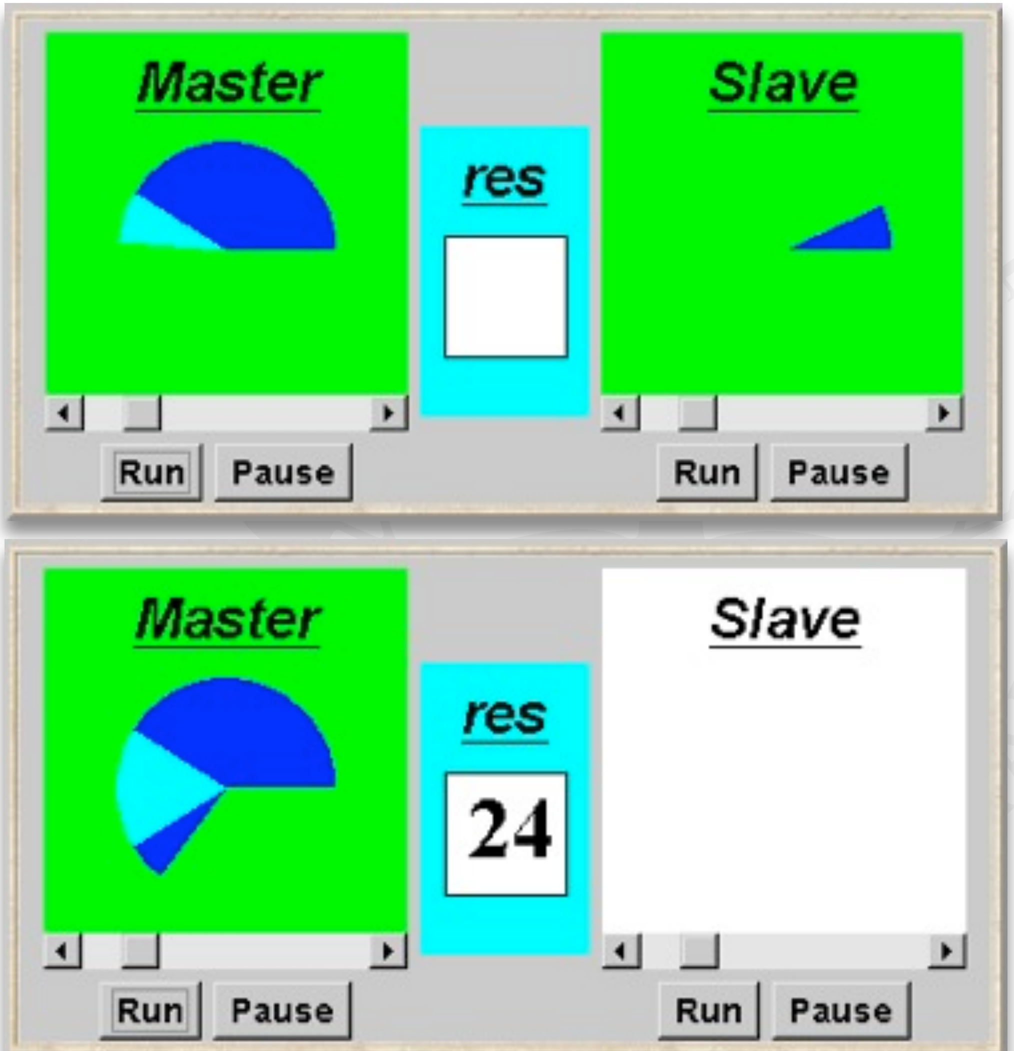
9.7 Master-Slave Program

A Master thread creates a Slave thread to perform some task (eg. I/O) and continues.

Later, the Master synchronizes with the Slave to collect the result.

How can we avoid busy waiting for the Master?

Java class `Thread` provides method `join()` which waits for the thread to die, i.e., by returning from `run()` or as a result of `stop()`.



Java Implementation - Master-Slave


```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
  SlotCanvas  resultDisplay;

  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
```

Java Implementation - Master-Slave

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```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
  SlotCanvas  resultDisplay;

  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
        if (res!=null) resultDisplay.leave(res);
```

Java Implementation - Master-Slave


```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
  SlotCanvas  resultDisplay;

  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
        if (res!=null) resultDisplay.leave(res);
        Slave s = new Slave();        // create new slave thread
        Thread st = slaveDisplay.start(s,false);
```

Slave thread is created and started using the `ThreadPanel` method `start`.

Java Implementation - Master-Slave


```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
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  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
        if (res!=null) resultDisplay.leave(res);
        Slave s = new Slave();        // create new slave thread
        Thread st = slaveDisplay.start(s,false);
        while (ThreadPanel.rotate()); // continue execution
```

Slave thread is created and started using the ThreadPanel method start.

Java Implementation - Master-Slave


```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
  SlotCanvas  resultDisplay;

  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
        if (res!=null) resultDisplay.leave(res);
        Slave s = new Slave();          // create new slave thread
        Thread st = slaveDisplay.start(s,false);
        while (ThreadPanel.rotate()); // continue execution
        st.join();                      // wait for slave termination
```

Slave thread is created and started using the `ThreadPanel` method `start`.

Java Implementation - Master-Slave

University of Southern Denmark

```
class Master implements Runnable {
  ThreadPanel slaveDisplay;
  SlotCanvas  resultDisplay;

  Master(ThreadPanel tp, SlotCanvas sc)
    {slaveDisplay=tp; resultDisplay=sc;}

  public void run() {
    try {
      String res=null;
      while(true) {
        while (!ThreadPanel.rotate());
        if (res!=null) resultDisplay.leave(res);
        Slave s = new Slave();          // create new slave thread
        Thread st = slaveDisplay.start(s,false);
        while (ThreadPanel.rotate()); // continue execution
        st.join();                      // wait for slave termination
        res = String.valueOf(s.result()); //get and display result from slave
        resultDisplay.enter(res);
      }
    } catch (InterruptedException e){}
  }
}
```

Slave thread is created and started using the `ThreadPanel` method `start`.

Java Implementation - Master-Slave

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```
class Slave implements Runnable {
  int rotations = 0;

 public void run() {
    try {
      while (!ThreadPanel.rotate()) ++rotations;
    } catch (InterruptedException e){}
  }

  int result(){
    return rotations;
  }
}
```

Slave method `result` need not be synchronized to avoid interference with the Master thread. **Why not?**

9.8 Master-Slave Model


```
SLAVE = (start->rotate->join->SLAVE).

MASTER = (slave.start->rotate
         ->slave.join->rotate->MASTER).

||MASTER_SLAVE = (MASTER || slave:SLAVE).
```

join is modeled by a synchronized action.

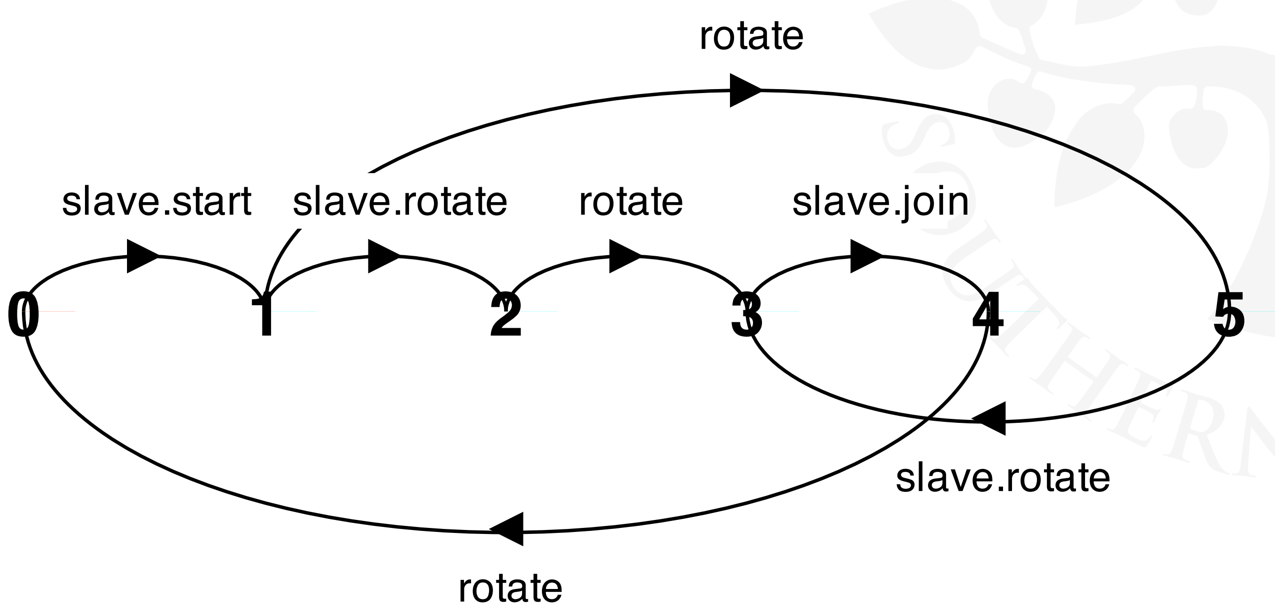
9.8 Master-Slave Model

```
SLAVE = (start->rotate->join->SLAVE).

MASTER = (slave.start->rotate
         ->slave.join->rotate->MASTER).

||MASTER_SLAVE = (MASTER || slave:SLAVE).
```

join is modeled by a synchronized action.



slave.rotate and rotate are interleaved, i.e., concurrent

Dynamic Systems

Dynamic Systems

Concepts: **dynamic** creation and deletion of **processes**

Resource allocation example – varying number of users and resources.

master-slave interaction

Dynamic Systems

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interaction

Practice: dynamic creation and deletion of threads

(# active threads varies during execution)

Resource allocation algorithms

Java join() method