3. Monitors in general and in Java
Communication and synchronization of parallel processes

Communication between parallel processes: exchange of data by

- using a common, global variable,
  only in a programming model with **common storage**
- **messages** in programming model **distributed** or **common storage**
  synchronous messages: sender waits for the receiver (languages: CSP, Occam, Ada, SR)
  asynchronous messages: sender does not wait for the receiver (languages: SR)

Synchronization of parallel processes:

- **mutual exclusion (gegenseitiger Ausschluss):**
  certain statement sequences (critical regions) may not be executed by several processes at the same time
- **condition synchronization (Bedingungssynchronisation):**
  a process waits until a certain condition is satisfied by a different process

Language constructs for synchronization:
Semaphore, monitor, condition variable (programming model with common storage)
messages (see above)

Deadlock (Verklemmung):
Some processes are waiting cyclically for each other, and are thus blocked forever

Monitor - general concept

Monitor: high level synchronization concept introduced in
[C.A.R. Hoare 1974, P. Brinch Hansen 1975]

Definition:

- A monitor is a **program module** for concurrent programming with **common storage**; it encapsulates data with its operations.
- A monitor has **entry procedures** (which operate on its data); they are **called by processes**; the monitor is **passive.**
- The monitor guarantees **mutual exclusion for calls of entry procedures:** at most one process executes an entry procedure at any time.
- **Condition variables** are defined in the monitor and are used within entry procedures for **condition synchronization**.

Condition variables

A **condition variable** c is defined to have 2 operations to operate on it.
They are executed by processes when executing a call of an entry procedure.

- **wait (c)** The executing process **leaves the monitor** and waits in a set associated to c, until it is released by a subsequent call signal(c); then the process accesses the monitor again and continues.
- **signal (c):** The executing process releases **one arbitrary process** that waits for c.

  Which of the two processes immediately continues its execution in the monitor depends on the variant of the signal semantics (see PPJ-22).
  signal-and-continue:
  The signal executing process continues its execution in the monitor.

  A call signal (c) has **no effect, if no process is waiting** for c.

Condition synchronization usually has the form

`if not B then wait (c);` or **`while not B do wait (c);`**

The **condition variable c** is used to synchronize on the **condition B**.

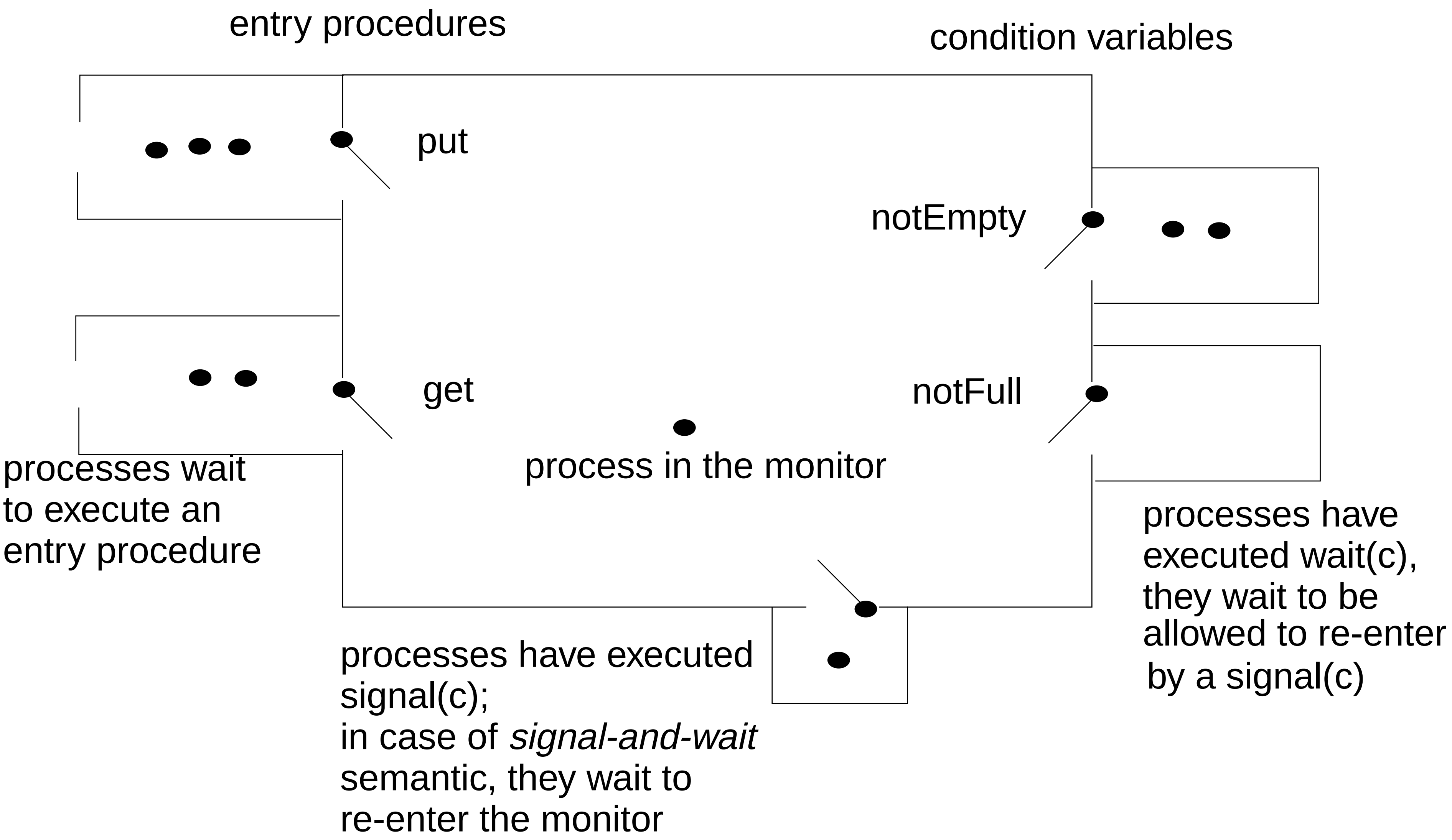
Note the difference between condition variables and semaphores:
Semaphores are counters. The effect of a call V(s) on a semaphore is not lost if no process is waiting on s.

Example: bounded buffer

```
monitor Buffer
   buf: Queue (k);
   notFull, notEmpty: Condition;

   entry put (d: Data)
      do length(buf) = k -> wait (notFull); od;
      enqueue (buf, d);
      signal (notEmpty);
   end;

   entry get (var d: Data)
      do length (buf) = 0 -> wait (notEmpty); od;
      d := front (buf); dequeue (buf);
      signal (notFull);
   end;
end;

process Producer (i: 1..n) d: Data;
   loop d := produce(); Buffer.put(d); end;
end;

process Consumer (i: 1..m) d: Data;
   loop Buffer.get(d); consume(d); end;
end;
```

2 condition variables: state of the buffer

Synchronization in a monitor



entry procedures

condition variables

put

get

notEmpty

notFull

process in the monitor

processes wait
to execute an
entry procedure

processes have
executed wait(c),
they wait to be
allowed to re-enter
by a signal(c)

processes have executed
signal(c);
in case of *signal-and-wait*
semantic, they wait to
re-enter the monitor

Variants of signal-wait semantics

Processes compete for the monitor

- processes that are blocked by executing **`wait(c)`**,
- process that is in the monitor, may be executing **`signal(c)`**
- processes that wait to execute an entry procedure

signal-and-exit semantics:
The process that executes **`signal`** terminates the entry procedure call and
leaves the monitor.
The released process enters the monitor **immediately** - without a state change in between

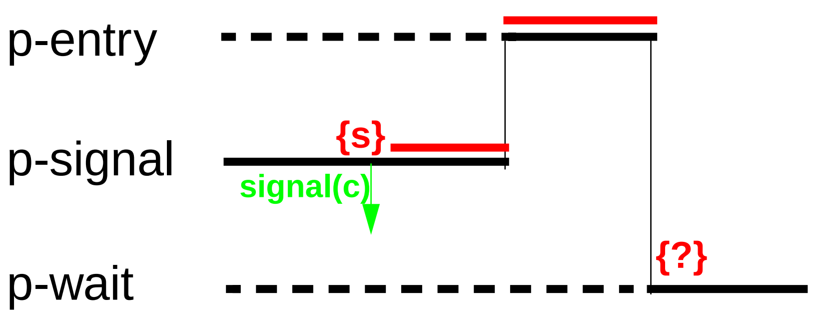
signal-and-wait semantics:
The process that executes **`signal`** leaves the monitor and waits to re-enter the monitor.
The released process enters the monitor **immediately** - without a state change in between
Variant **signal-and-urgent-wait**:
The process that has executed signal gets a higher priority
than processes waiting for entry procedures

signal-and-continue semantics:
The process that executes signal continues execution in the monitor.
The released process has to wait until the monitor is free. The **state** that held at the **`signal`** call may be changed meanwhile; the waiting condition has to be checked again:

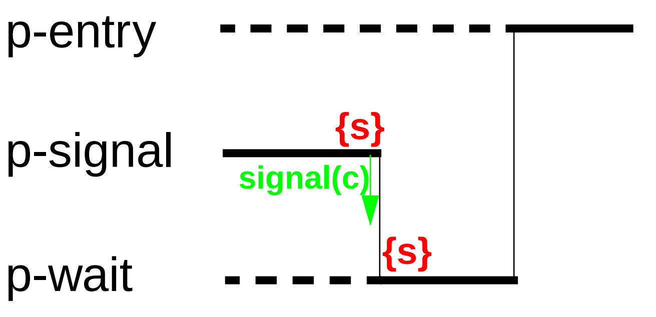
```
do length(buf) = k -> wait(notFull); od;
```

Variants of signal-wait semantics: examples of execution

signal-and-continue



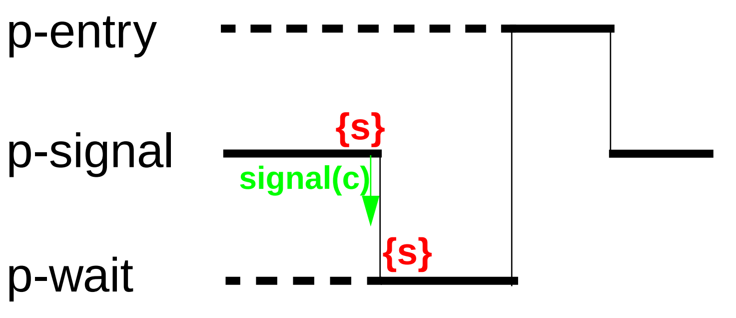
signal-and-exit



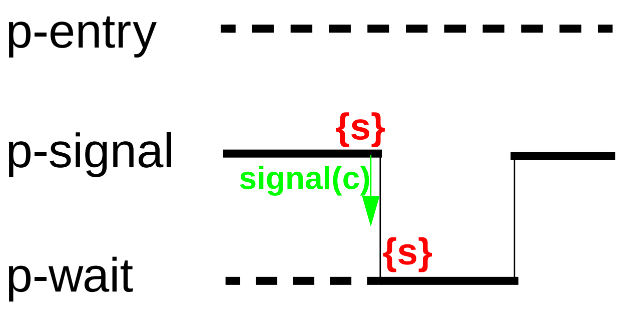
3 processes:
p-entry waits to enter an entry procedure
p-signal executes **signal(c)**
p-wait has executed **wait(c)**

{s} state when **signal(c)** is executed
{s} may be modified here: ▬

signal-and-wait



signal-and-urgent-wait



Monitors in Java: mutual exclusion

Objects of any class can be used as **monitors**

Entry procedures:

Methods of a class, which implement critical operations on instance variables can be marked **`synchronized`**:

```
class Buffer
{  synchronized public void put (Data d) {...}
   synchronized public Data get () {...}
   ...
   private Queue buf;
}
```

If several processes **call `synchronized` methods** for the same object, they are executed under **mutual exclusion**.
They are synchronized by an internal synchronization variable of the object (lock).

Non-**`synchronized`** methods can be executed at any time concurrently.

There are also **`synchronized` class methods**: they are called under mutual exclusion with respect to the class.

`synchronized` blocks can be used to specify execution of a critical region with respect to an arbitrary object.

Monitors in Java: condition synchronization

All processes that are blocked by **`wait`** are held in a single set;
condition variables can not be declared (there is only an implicit one)

Operations for condition synchronization:
are to be called from inside **`synchronized`** methods:

- **`wait()`** **blocks** the executing process;
  releases the monitor object, and
  waits in the unique set of blocked processes of the object
- **`notifyAll()`** releases **all** processes that are blocked by **`wait`** for this object;
  they then compete for the monitor;
  the executing process continues in the monitor
  (signal-and-continue semantics).
- **`notify()`** releases **an arbitrary** one of the processes that are blocked by **`wait`**
  for this object;
  the executing process continues in the monitor
  (signal-and-continue semantics);
  only usable if all processes wait for the same condition.

Always call `wait` in loops, because with **signal-and-continue** semantics
after **`notify`, `notifyAll`** the **waiting condition may be changed:**

```
while (!Condition) try { wait(); } catch (InterruptedException e) {}
```

A Monitor class for bounded buffers

```
class Buffer
{  private Queue buf;                 // Queue of length n to store the elements
   public Buffer (int n) {buf = new Queue(n); }

   synchronized public void put (Object elem)
   {                               // a producer process tries to store an element
      while (buf.isFull())                       // waits while the buffer is full
         try {wait();} catch (InterruptedException e) {}
      buf.enqueue (elem);     // changes the waiting condition of the get method
      notifyAll();           // every blocked process checks its waiting condition
   }
   synchronized public Object get ()
   {                               // a consumer process tries to take an element
      while (buf.isEmpty())                     // waits while the buffer is empty
         try {wait();} catch (InterruptedException e) {}
      Object elem = buf.first();
      buf.dequeue();           // changes the waiting condition of the put method
      notifyAll();           // every blocked process checks its waiting condition
      return elem;
   }
}
```

Concurrency Utilities in Java 2

The **Java 2 platform** includes a package of *concurrency utilities*. These are classes which are designed to be used as building blocks in building concurrent classes or applications. ...

...

Locks - While locking is built into the Java language via the synchronized keyword, there are a number of **inconvenient limitations to built-in monitor locks**. The **`java.util.concurrent.locks`** package provides a high-performance lock implementation with **the same memory semantics as synchronization**, but which also supports specifying a timeout when attempting to acquire a lock, multiple condition variables per lock, non-lexically scoped locks, and support for interrupting threads which are waiting to acquire a lock.

`http://java.sun.com/j2se/1.5.0/docs/guide/concurrency/index.html`

`http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/locks/Condition.html`

Concurrency Utilities in Java 2 (example)

```
class BoundedBuffer {
    final Lock lock = new ReentrantLock();                              explicit lock
    final Condition notFull  = lock.newCondition();               condition variables
    final Condition notEmpty = lock.newCondition();

    final Object[] items = new Object[100];
    int putptr, takeptr, count;

    public void put (Object x) throws InterruptedException {
        lock.lock();                                        explicit mutual exclusion
        try {  while (count == items.length) notFull.await();           specific wait
               items[putptr] = x;
               if (++putptr == items.length) putptr = 0;
               ++count;
               notEmpty.signal();                                     specific signal
        } finally { lock.unlock();}                         explicit mutual exclusion
    }

    public Object get () throws InterruptedException {
        lock.lock();                                        explicit mutual exclusion
        try {  while (count == 0) notEmpty.await();                     specific wait
               Object x = items[takeptr];
               if (++takeptr == items.length) takeptr = 0;
               --count;
               notFull.signal();                                      specific signal
               return x;
        } finally { lock.unlock();}                         explicit mutual exclusion
    }
}
```

3. Systematic Development of monitors
Monitor invariant

A **monitor invariant (MI)** specifies **acceptable states of a monitor**

MI has to be true whenever a process may leave or (re-)enter the monitor:

- after the **initialization**,
- at the **beginning** and at the **end of each entry procedure**,
- before and after each call of **wait**,
- before and after each call of **signal** with **signal-and-wait** semantics (*),
- before each call of **signal** with **signal-and-exit** semantics (*).

Example of a monitor invariant for the bounded buffer:

MI: 0 <= buf.length() <= n

The **monitor invariant has to be proven** for the program positions
after the initialization, at the end of entry procedures, before calls of wait (and signal if (*)).

One can **assume that the monitor invariant holds** at the other positions
at the beginning of entry procedures, after calls of wait (and signal if (*)).

Design steps using monitor invariant

1. Define the **monitor state,** and design the **entry procedures without synchronization**
   e. g. bounded buffer: element count; entry procedures put and get

2. Specify a **monitor invariant**
   e. g.: **MI**: **`0 <= length(buf) <= N`**

3. Insert **conditional waits**:
   Consider every operation that may violate **MI**, e. g. **`enqueue(buf)`**;
   find a condition **Cond** such that the operation may be executed safely if **Cond && MI** holds,
   e. g. **`{ length(buf)<N && MI } enqueue(buf);`**
   define one condition variable **`c`** for each condition Cond
   insert a conditional wait in front of the operation:
   `do !(length(buf)<N) -> wait(c); od`
   Loop is necessary in case of signal-and-continue or the may in step 4!

4. **Insert notification of processes:**
   after every state change that may make a waiting condition **Cond** true insert
   `signal(c)` for the condition variable **`c`** of Cond
   e. g. **`dequeue(buf); signal (c);`**
   Too many signal calls do not influence correctness - they only cause inefficiency.

5. **Eliminate unnecessary calls of `signal`** (see PPJ-28)
   Caution: Missing signal calls may cause deadlocks!
   Caution: signal-and-continue semantics lacks control of state changes

Bounded buffers
Derivation step 1: monitor state and entry procedures

```
monitor Buffer
   buf: Queue;                                   // state: buf, length(buf)

   init buf = new Queue(n); end
   entry put (d: Data)              // a producer process tries to store an element


      enqueue (buf, d);

   end;
   entry get (var d: Data)          // a consumer process tries to take an element


      d := front(buf);
      dequeue(buf);

   end;
end;
```

Bounded buffers
Derivation step 2: monitor invariant MI

```
monitor Buffer
   buf: Queue;                                    // state: buf, length(buf)

   init buf = new Queue(n); end                   // MI: 0 <= length(buf) <= N
   entry put (d: Data)                  // a producer process tries to store an element


      enqueue (buf, d);

   end;
   entry get (var d: Data)              // a consumer process tries to take an element


      d := front(buf);
      dequeue(buf);

   end;
end;
```

Bounded buffers
Derivation step 3: insert conditional waits

```
monitor Buffer
   buf: Queue;                                        // state: buf, length(buf)
   notFull, notEmpty: Condition;
   init buf = new Queue(n); end                       // MI: 0 <= length(buf) <= N
   entry put (d: Data)            // a producer process tries to store an element

      /* length(buf) < N && MI */
      enqueue (buf, d);

   end;
   entry get (var d: Data)        // a consumer process tries to take an element

      /* length(buf) > 0 && MI */
      d := front(buf);
      dequeue(buf);

   end;
end;
```

Bounded buffers
Derivation step 3: insert conditional waits

```
monitor Buffer
   buf: Queue;                                     // state: buf, length(buf)
   notFull, notEmpty: Condition;
   init buf = new Queue(n); end                    // MI: 0 <= length(buf) <= N
   entry put (d: Data)              // a producer process tries to store an element
      do length(buf) >= N -> wait(notFull); od;
      /* length(buf) < N && MI */
      enqueue (buf, d);

   end;
   entry get (var d: Data)          // a consumer process tries to take an element
      do length(buf) <= 0 -> wait(notEmpty); od;
      /* length(buf) > 0 && MI */
      d := front(buf);
      dequeue(buf);

   end;
end;
```

Bounded buffers
Derivation step 4: insert notifications

```
monitor Buffer
   buf: Queue;                                      // state: buf, length(buf)
   notFull, notEmpty: Condition;
   init buf = new Queue(n); end                     // MI: 0 <= length(buf) <= N
   entry put (d: Data)              // a producer process tries to store an element
      do length(buf) >= N -> wait(notFull); od;
      /* length(buf) < N && MI */
      enqueue (buf, d);
      /* length(buf)>0 */
   end;
   entry get (var d: Data)          // a consumer process tries to take an element
      do length(buf) <= 0 -> wait(notEmpty); od;
      /* length(buf) > 0 && MI */
      d := front(buf);
      dequeue(buf);
      /* length(buf)<N */
   end;
end;
```

Bounded buffers
Derivation step 4: insert notifications

```
monitor Buffer
   buf: Queue;                                      // state: buf, length(buf)

   notFull, notEmpty: Condition;

   init buf = new Queue(n); end                     // MI: 0 <= length(buf) <= N

   entry put (d: Data)              // a producer process tries to store an element
      do length(buf) >= N -> wait(notFull); od;
      /* length(buf) < N && MI */
      enqueue (buf, d);
      /* length(buf)>0 */ signal(notEmpty);
   end;

   entry get (var d: Data)          // a consumer process tries to take an element
      do length(buf) <= 0 -> wait(notEmpty); od;
      /* length(buf) > 0 && MI */
      d := front(buf);
      dequeue(buf);
      /* length(buf)<N */ signal(notFull);
   end;
end;
```

Bounded buffers
Derivation step 5: eliminate unnecessary notifications

```
monitor Buffer
   buf: Queue;                                  // state: buf, length(buf)
   notFull, notEmpty: Condition;
   init buf = new Queue(n); end                 // MI: 0 <= length(buf) <= N
   entry put (d: Data)          // a producer process tries to store an element
      do length(buf) >= N -> wait(notFull); od;
      /* length(buf) < N && MI */
      enqueue (buf, d);
      if (length(buf) == 1) signal(notEmpty);               // see PPJ-28
                                     // not correct under signal-and-continue
   end;
   entry get (var d: Data)      // a consumer process tries to take an element
      do length(buf) <= 0 -> wait(notEmpty); od;
      /* length(buf) > 0 && MI */
      d := front(buf);
      dequeue(buf);
      if length(buf) == (N-1) -> signal(notFull);           // see PPJ-28
                                     // not correct under signal-and-continue
   end;
end;
```

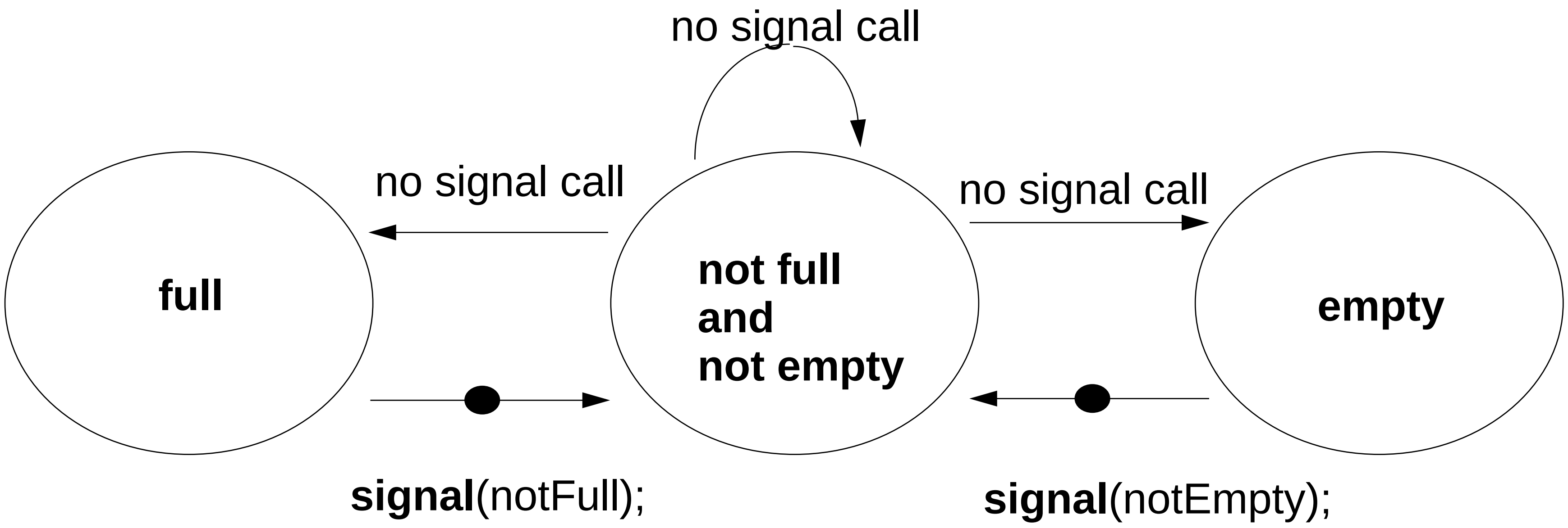
Relevant state changes

Processes need only be awakened when the state change is relevant:

when the waiting condition Cond changes from false to true,
i.e. when a waiting process can be released.

These arguments do **not** apply for **signal-and-continue** semantics; there **Cond** may be changed between the signal call and the resume of the released process.

E. g. for the bounded buffer states w.r.t signalling are considered:



Pattern: Allocating counted resources

A **monitor** grants access to a set of k ≥ 1 resources of the **same kind**.
Processes request n resources, 1≤ n ≤ k, and return them after having used them.
Examples:
Lending bikes in groups (n ≥ 1), allocating blocks of storage (n ≥ 1),
Taxicab provider (n=1), drive with a weight of n ≥ 1 tons on a bridge

Monitor invariant	**requestRes(1)**	**returnRes(1)**
0 ≤ avail don’t give a non-ex. resource	if/do (!(1≤avail)) wait(av); avail--;	avail++; /* no wait! */ signal(av);
stronger invariant:		

0 ≤ avail && 0 ≤ inUse
... and don’t take back more than have been given
	if/do (!(1≤avail)) wait(av);
	avail--; inUse++;
	signal(iu);
		if/do (!(1≤inUse)) wait(iu);
		avail++; inUse--;
		signal(av);

Monitor invariant	**requestRes(n)**	**returnRes(n)**
0 ≤ avail don’t give a non-ex. resource	do (!(n≤avail)) wait(av[n]); avail = avail - n;	avail = avail + n; /* no wait! */ signal(av[1]); ... signal(av[avail]);

The **identity** of the resources may be relevant: use a boolean array avail[1] ... avail[k]

Monitor for resource allocation

A **monitor** grants access to a set of k >= 1 resources of the **same kind**.
Processes request n resources, 1<=n<=k, and return them after having used them.

Assumption: Process does not return more than it has received => simpler invariant:

```
class Resources
{  private int avail;                                    // invariant: avail >= 0

   public Resources (int k) { avail = k; }

   synchronized public void getElems (int n)             // request n elements
   {  while (avail<n)                                    // negated waiting condition
         try { wait(); } catch (InterruptedException e) {}
      avail -= n;
   }

   synchronized public void putElems (int n)             // return n elements
   {  avail += n;                    // waiting is not needed because of assumption
      notifyAll();                                       // notify() would be wrong!
   }
}
```

Processes and main program for resource monitor

```
import java.util.Random;

class Client extends Thread
{  private Resources mon; private Random rand;
   private int ident, rounds, maximum;

   public Client (Resources m, int id, int rd, int max)
   {  mon = m; ident = id; rounds = rd; maximum = max;
      rand = new Random();             // a number generator determines how many
   }                                      // elements are requested in each round,

   public void run ()                            // and when they are returned
   {  while (rounds > 0)
      {  int m = Math.abs(rand.nextInt()) % maximum + 1;
         mon.getElems (m);
         try { sleep (Math.abs(rand.nextInt()) % 1000 + 1); }
            catch (InterruptedException e) {}
         mon.putElems (m);
         rounds--;
      }
   }
}
```

```
public class TestResource
{ public static void main (String[] args)
  { int avail = 20;
    Resources mon = new Resources (avail);
    for (int i=0; i<5; i++)
      new Client (mon, i, 4, avail).start();
  }
}
```

Readers-Writers problem (Step 1)

A monitor grants reading and writing access to a data base:
readers shared, **writers exclusive**.

```
monitor ReadersWriters
   nr: int;   // number readers
   nw: int;   // number writers
init nr=0; nw=0; end

entry requestRead()




   nr++;

end;

entry releaseRead()
   nr--;



end;
```

```
entry requestWrite()




   nw++;

end;

entry releaseWrite()
   nw--;



end;
end;
```

Readers-Writers problem (Step 2)

A monitor grants reading and writing access to a data base:
readers shared, **writers exclusive**.

```
monitor ReadersWriters
   nr: int;   // number readers
   nw: int;   // number writers
init nr=0; nw=0; end

entry requestRead()





   nr++;

end;

entry releaseRead()
   nr--;




end;
```

Monitor invariant RW:

(nr == 0 || nw == 0) && nw <= 1

```
entry requestWrite()





   nw++;

end;

entry releaseWrite()
   nw--;




end;
end;
```

Readers-Writers problem (Step3)

A monitor grants reading and writing access to a data base:
readers shared, **writers exclusive**.

Monitor invariant RW:

(nr == 0 || nw == 0) && nw <= 1

```
monitor ReadersWriters
   nr: int;   // number readers
   nw: int;   // number writers
init nr=0; nw=0; end

entry requestRead()
   do !(nw==0)
      -> wait(okToRead);
   od;
   { nw==0 && RW }
   nr++;
   { RW }
end;

entry releaseRead()
   { RW && nr>0} nr--;




end;
```

```
entry requestWrite()
   do !(nr==0 && nw<1)
      -> wait(okToWrite);
   od;
   { nr==0 && nw<1 && RW }
   nw++;
   { RW }
end;

entry releaseWrite()
   { RW && nw==1} nw--;



end;
end;
```

Readers-Writers problem (Step 4)

A monitor grants reading and writing access to a data base:
readers shared, **writers exclusive**.

Monitor invariant RW:

(nr == 0 || nw == 0) && nw <= 1

```
monitor ReadersWriters
   nr: int;   // number readers
   nw: int;   // number writers
init nr=0; nw=0; end

entry requestRead()
   do !(nw==0)
      -> wait(okToRead);
   od;
   { nw==0 && RW }
   nr++;
   { RW }
end;

entry releaseRead()
   { RW && nr>0} nr--;
   { RW && nr>=0}
   { may be nr==0}

   signal(okToWrite);
end;
```

```
entry requestWrite()
   do !(nr==0 && nw<1)
      -> wait(okToWrite);
   od;
   { nr==0 && nw<1 && RW }
   nw++;
   { RW }
end;

entry releaseWrite()
   { RW && nw==1} nw--;
   { nr==0 && nw==0}
   signal(okToWrite);
   signal_all(okToRead);
end;
end;
```

Readers-Writers problem (Step 5)

A monitor grants reading and writing access to a data base:
readers shared, **writers exclusive**.

Monitor invariant RW:

(nr == 0 || nw == 0) && nw <= 1

```
monitor ReadersWriters
   nr: int;   // number readers
   nw: int;   // number writers
init nr=0; nw=0; end

entry requestRead()
   do !(nw==0)
      -> wait(okToRead);
   od;
   { nw==0 && RW }
   nr++;
   { RW }
end;

entry releaseRead()
   { RW && nr>0} nr--;
   { RW && nr>=0}
   { may be nr==0}
   if nr==0
   -> signal(okToWrite);
end;
```

```
entry requestWrite()
   do !(nr==0 && nw<1)
      -> wait(okToWrite);
   od;
   { nr==0 && nw<1 && RW }
   nw++;
   { RW }
end;

entry releaseWrite()
   { RW && nw==1} nw--;
   { nr==0 && nw==0}
   signal(okToWrite);
   signal_all(okToRead);
end;
end;
```

Readers/writers monitor in Java

```
class ReaderWriter
{  private int nr = 0, nw = 0;
                    // monitor invariant RW: (nr == 0 || nw == 0) && nw <= 1
   synchronized public void requestRead ()
   {  while (nw > 0)                                    // negated waiting condition
         try { wait(); } catch (InterruptedException e) {}
      nr++;
   }
   synchronized public void releaseRead ()
   {  nr--;
      if (nr == 0) notify ();                          // awaken one writer is sufficient
   }

   synchronized public void requestWrite ()
   {  while (nr > 0 || nw > 0)                          // negated waiting condition
         try { wait(); } catch (InterruptedException e) {}
      nw++;
   }
   synchronized public void releaseWrite ()
   {  nw--;
      notifyAll ();                   // notify 1 writer and all readers would be sufficient!
   }
}
```

Method: rendezvous of processes

Processes pass through a **sequence of states** and **interact** with each other.
A monitor coordinates the **rendezvous in the required order**.

Design method:
Specify states by counters;
characterize **allowed states by invariants** over counters;
derive waiting conditions of monitor operations from the invariants;
substitute counters by binary variables.

Example: Sleeping Barber:

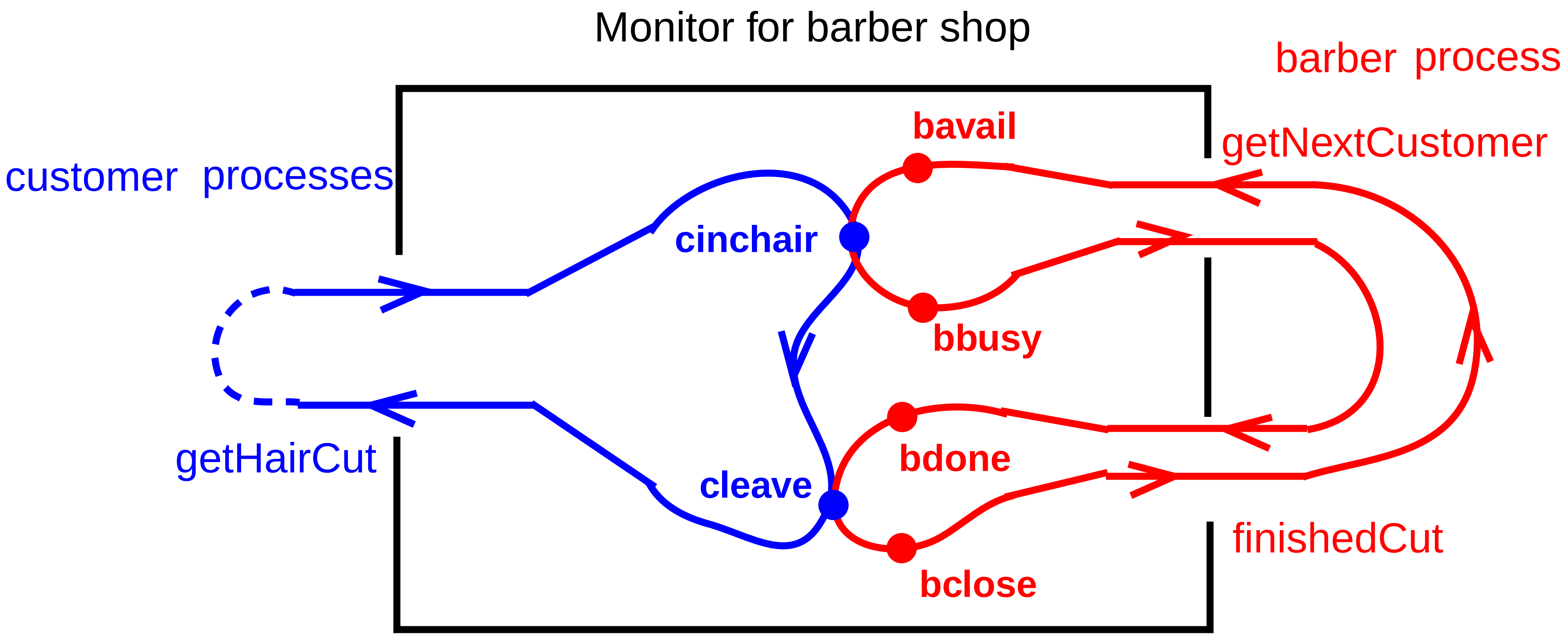
In a sleepy village close to Paderborn a barber is sleeping while waiting for customers to enter his shop. When a customer arrives and finds the barber sleeping, he awakens him, sits in the barber‘s chair, and sleeps while he gets his hair cut. If the barber is busy when a customer arrives, the customer sleeps in one of the other chairs. After finishing the haircut, the barber gets paid, lets the customer exit, and awakens a waiting customer, if any.

2 kinds of processes: barber (1 instance), customer (many instances)

2 rendezvous: haircut and customer leaves

The task is also an example for the Client/Server pattern.

Monitor design for the Sleeping Barber problem (step 1)



Counters represent states, incremented in entry procedures:

entry proc getHairCut:

cinchair++;
cleave++;

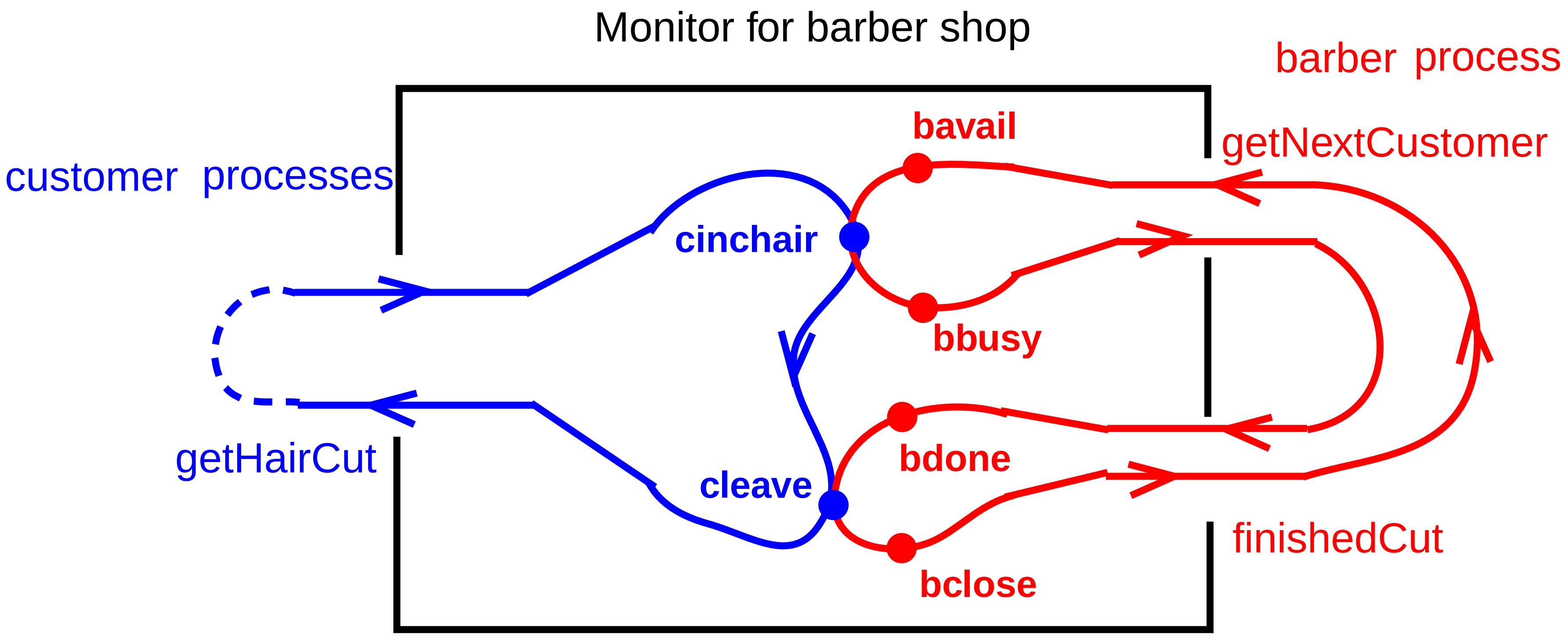
entry proc getNextCustomer:

bavail++;
bbusy++;

entry proc finishedCut:

bdone++;
bclose++;

Monitor invariant for the Sleeping Barber problem (step 2)



Invariants over counters:

C1: cinchair >= cleave and
bavail >= bbusy >= bdone >= bclose

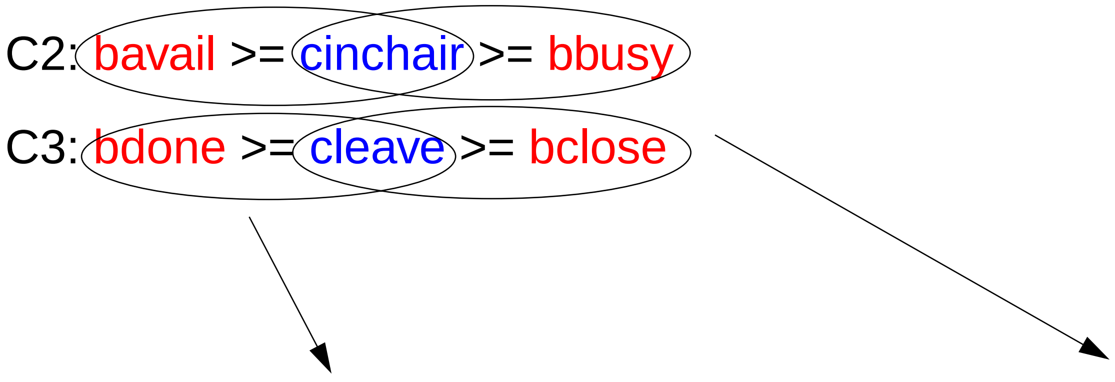
C2: bavail >= cinchair >= bbusy

C3: bdone >= cleave >= bclose

Monitor invariant: BARBER: C1 and C2 and C3

Waiting conditions for the Sleeping Barber problem (step 3)

Monitor invariant: BARBER: C1 and C2 and C3:



C1: cinchair >= cleave and
bavail >= bbusy >= bdone >= bclose
guaranteed by execution order

C2: bavail >= cinchair >= bbusy
leads to 2 waiting conditions

C3: bdone >= cleave >= bclose
leads to 2 waiting conditions

```
entry proc getHairCut:

    do not (bavail > cinchair) -> wait (b); done;
    cinchair++;

    do not (bdone > cleave) -> wait (o); done;
    cleave++;
```

```
entry proc getNextCustomer:

    bavail++;

    do not (cinchair > bbusy) -> wait (c); done;
    bbusy++;

entry proc finishedCut:

    bdone++;

    do not (cleave > bclose) -> wait (e); done;
    bclose++;
```

Substitute counters (step 3a)

new binary variables:

barber = bavail - cinchair
chair = cinchair - bbusy
open = bdone - cleave
exit = cleave - bclose

value ranges: {0, 1}

Old invariants:

C2: bavail >= cinchair >= bbusy
C3: bdone >= cleave >= bclose

New invariants:

C2: barber >= 0 && chair >= 0
C3: open >= 0 && exit >= 0

increment operations and conditions are substituted:

```
entry proc getHairCut:

   do not (barber > 0) -> wait (b); done;
   barber--; chair++;

   do not (open > 0) -> wait (o); done;
    open--; exit++;
```

```
entry proc getNextCustomer:

   barber++;

   do not (chair > 0) -> wait (c); done;
   chair--;

entry proc finishedCut:

   open++;

   do not (exit > 0) -> wait (e); done;
   exit--;
```

Signal operations for the Sleeping Barber problem (step 4)

new binary variables:
barber = bavail - cinchair
chair = cinchair - bbusy
open = bdone - cleave
exit = cleave - bclose

value ranges: {0, 1}

Old invariants:
C2: bavail >= cinchair >= bbusy
C3: bdone >= cleave >= bclose

New invariants:
C2: barber >= 0 && chair >= 0
C3: open >= 0 && exit >= 0

insert call signal (x) call where a condition of x may become true:

entry proc getHairCut:

do not (barber > 0) -> wait (b); done;
barber--; chair++; signal (c);

do not (open > 0) -> wait (o); done;
open--; exit++; signal (e);

entry proc getNextCustomer:

barber++; signal (b);

do not (chair > 0) -> wait (c); done;
chair--;

entry proc finishedCut:

open++; signal (o);

do not (exit > 0) -> wait (e); done;
exit--;