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Lecture 3:

Introduction to concurrency & SCOOP

The SCOOP programming model

Basic operation of OO programming: x.f (...)

Can be a command or a query:

```
r (c: separate CONFERENCE ; p: PAPER)      -- Exclusive access
  require
      c.submission_open                    -- Waiting
  do
      c.submit (p)                         -- Asynchronous
      ...
      if c.accepted (p) then rejoice end   -- Synchronous
  end
```

```
r (icse , latest)
  -- Exclusive access when needed
```

Four risks

Data race

- Incorrect concurrent access to shared data

Deadlock

- Computation cannot progress because of circular waiting

Starvation

- Execution favors certain processes over others, which never get executed

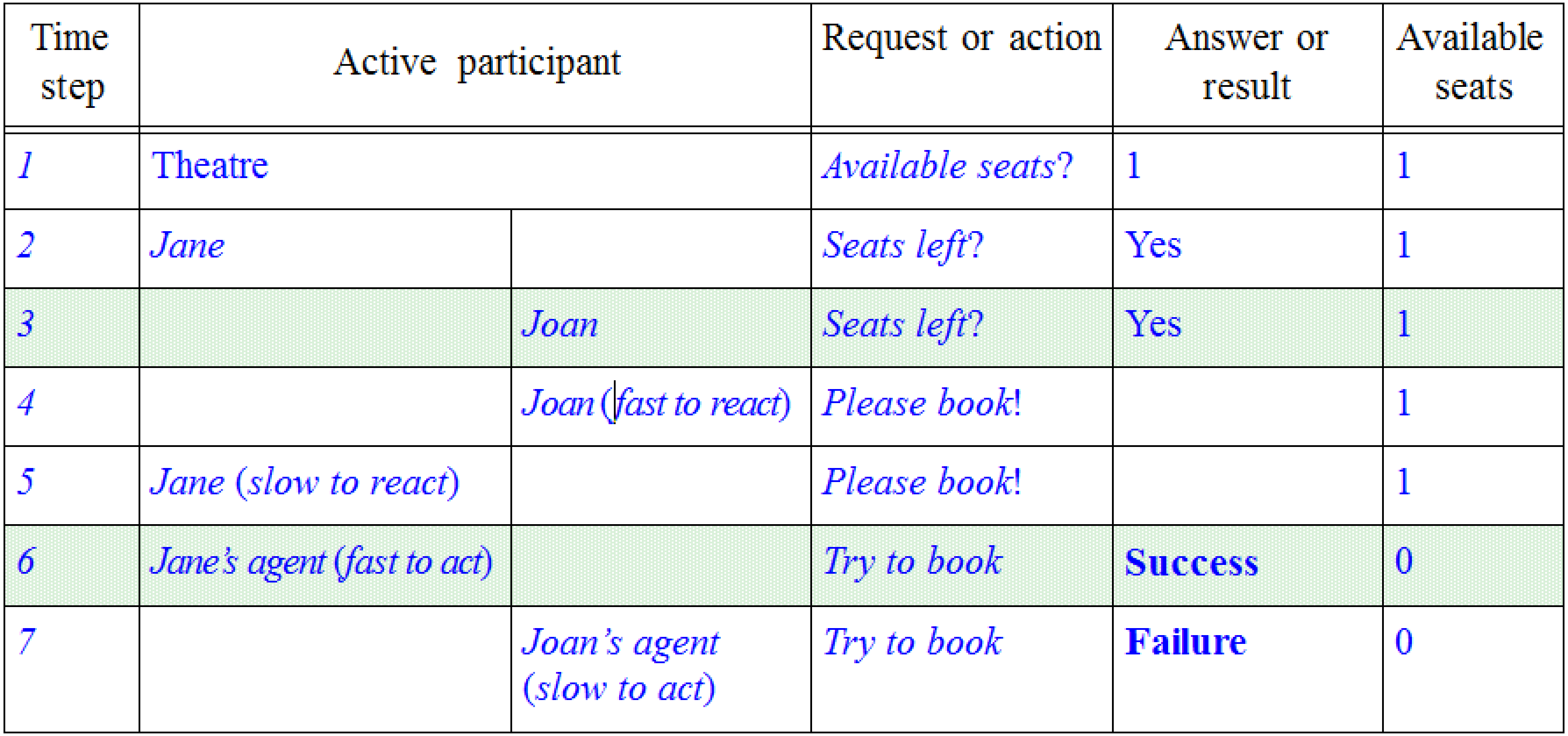
Priority inversion

- Locks cause a violation of priority rules

Data race

- *Thank you for calling Ecstatic Opera Company. How can I help you?*
- (Joan) I need a single seat for next Tuesday's performance of *Pique Dame.*
- *Let me check... You're in luck! Just one left. Eighty dollars.*
- Great. I'll go for it.
- *Just a moment while I book it.*
- Thanks.
- *Sorry, there are no more seats available for Tuesday.*

Data race: scenario



Time step	Active participant		Request or action	Answer or result	Available seats
1	Theatre		*Available seats?*	1	1
2	*Jane*		*Seats left?*	Yes	1
3		*Joan*	*Seats left?*	Yes	1
4		*Joan (fast to react)*	*Please book!*		1
5	*Jane (slow to react)*		*Please book!*		1
6	*Jane's agent (fast to act)*		*Try to book*	**Success**	0
7		*Joan's agent (slow to act)*	*Try to book*	**Failure**	0

Deadlock

(Jane)

- I'd like to change my Tuesday evening seat for the matinee performance.
- *Both shows are sold out, but I heard there was a customer who wanted to change the other way around. Matinee booking is handled by a different office, so let me call them and make the change.*
- Thanks.
- (Ten minutes later.) *"The number is still busy."*

Deadlock: scenario

Time step	Active participant		Request or action	Answer or result
1	*Agent 1*		*Matinee available for exchange?*	Yes
2		*Agent 2*	*Evening available for exchange?*	Yes
3	*Agent 1*		*Start dialing call to agent 2*	
4		*Agent 2*	*Start dialing call to agent 1*	
5	*Agent 1*		*Finish dialing*	Busy signal, because agent 2 is trying to call
6		*Agent 2*	*Finish dialing*	Busy signal, because agent 1 is trying to call
7	*Agent 1 & Agent 2*		*Repeat steps 3 to 6 forever as the result remains the same: busy signals*	

Starvation

Jane keeps calling, but agents always pick up someone else’s call

Execution sequences

x := 0			
P1		P2	
1 2	x := 0 x := x + 1	1	x := 2

- Execution can give rise to this *execution sequence*:

P1	1	x := 0	x = 0
P2	1	x := 2	x = 2
P1	2	x := x + 1	x = 3

Instruction executed with Thread ID and line number

Variable values after execution of the code on the line

Execution sequences

x := 0			
P1		P2	
1	x := 0	1	x := 2
2	x := x + 1		

Possible execution sequences considering all interleavings:

P2	1	x := 2	x = 2
P1	1	x := 0	x = 0
P1	2	x := x + 1	x = 1

P1	1	x := 0	x = 0
P2	1	x := 2	x = 2
P1	2	x := x + 1	x = 3

P1	1	x := 0	x = 0
P1	2	x := x + 1	x = 1
P2	1	x := 2	x = 2

Data races (race conditions)

If processes (OS processes, threads) are completely independent, concurrency is easy

Usually, however, threads *interfere* with each other by accessing and modifying common resources, such as variables and objects

- Unwanted dependency of the computation's result on nondeterministic interleaving is a *race condition* or *data race*
- Such errors can stay hidden for a long time and are difficult to find by testing

Dining philosophers

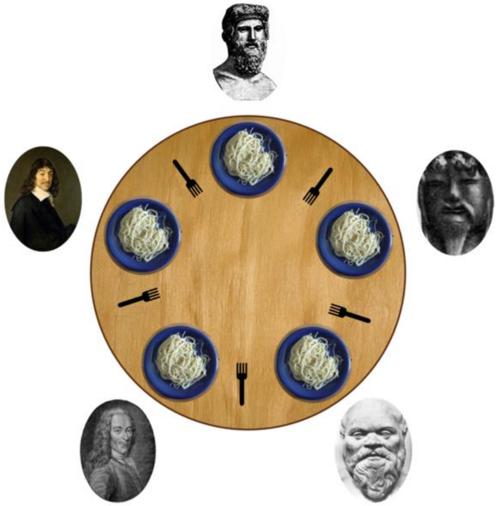
The dining philosophers problem

n philosophers are seated around a table; between each pair there is a single fork

Each philosopher only thinks and eats

To eat, a philosopher needs both left and right forks (so two adjacent philosophers cannot eat at the same time)

The problem: devise an algorithm enabling philosophers to follow this scheme, without deadlock



Dining philosophers: solution attempt 1

Each philosopher first picks up the right fork, then the left fork, and then starts eating; after having eaten, the philosopher puts down the left fork, then the right one

- The philosophers can deadlock!

Dining philosophers: solution attempt 2

Each philosopher successively:

- Picks up right fork and the left fork *at the same time*
- Starts eating
- After having eaten, puts them both back down

A philosopher could *starve!*

Fairness

To prove freedom from starvation or other liveness properties, fairness assumptions are sometimes needed

Fairness is concerned with a fair resolution of nondeterminism

- *Weak fairness:* if an action is *continuously enabled*, i.e. never temporarily disabled, then it has to be executed infinitely often
- *Strong fairness:* if an action is *infinitely often enabled*, but not necessarily always, then it has to be executed infinitely often

SCOOP background

Simple Concurrent Object-Oriented Programming

First version described in CACM article (1993) and chapter 32 of *Object-Oriented Software Construction*, 2nd edition, 1997

Prototype implementation at ETH (2005-2010)

Recent production implementation at Eiffel Software, part of EiffelStudio

Recent descriptions: Piotr Nienaltowski's 2007 ETH PhD; Morandi, Nanz, Meyer (2011)

Example 1: bank transfer, from sequential to concurrent

```
transfer (source, target: separate ACCOUNT;
          amount: INTEGER)
      -- Transfer amount, if available, from source to target.
   do
      if source.balance >= amount then
          source.withdraw  (amount)
          target.deposit   (amount)
      end
   end
```

```
transfer (Jane, Jill, 100)
transfer (Jane, Joan, 100)
```

Jane	Jill	Joan
100	0	0
0	100	0
-100	0	100

Bank transfer (better version)

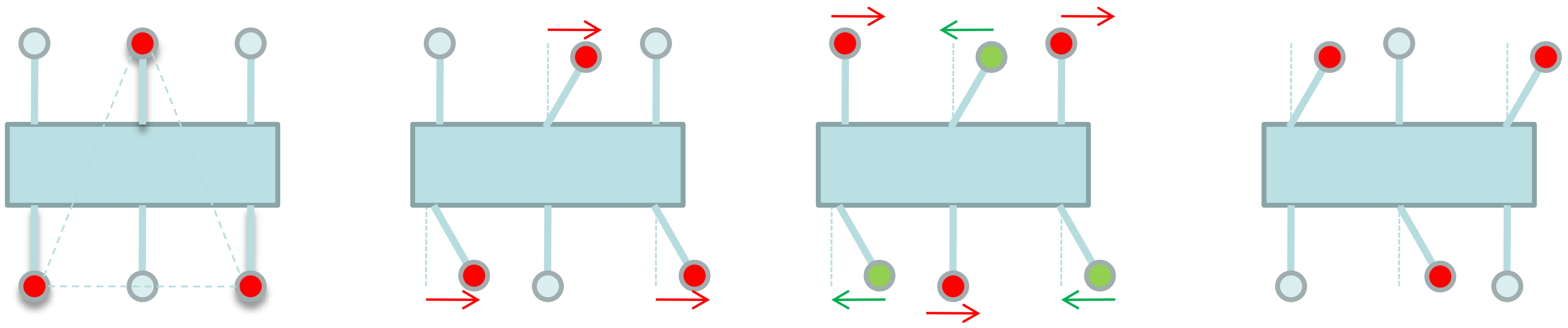
```
transfer (source, target: separate ACCOUNT;
              amount: INTEGER)
          -- Transfer amount from source to target.
     require
           source.balance >= amount
     do
          source.withdraw  (amount)
          target.deposit     (amount)
     ensure
          source.balance = old source.balance – amount
          target.balance = old target.balance + amount
     end
```

Example 2: hexapod robot

Hind legs have force sensors on feet and retraction limit switches

Hexapod locomotion

Ganesh Ramanathan, Benjamin Morandi, IROS 2011



Alternating protraction and retraction of tripod pairs

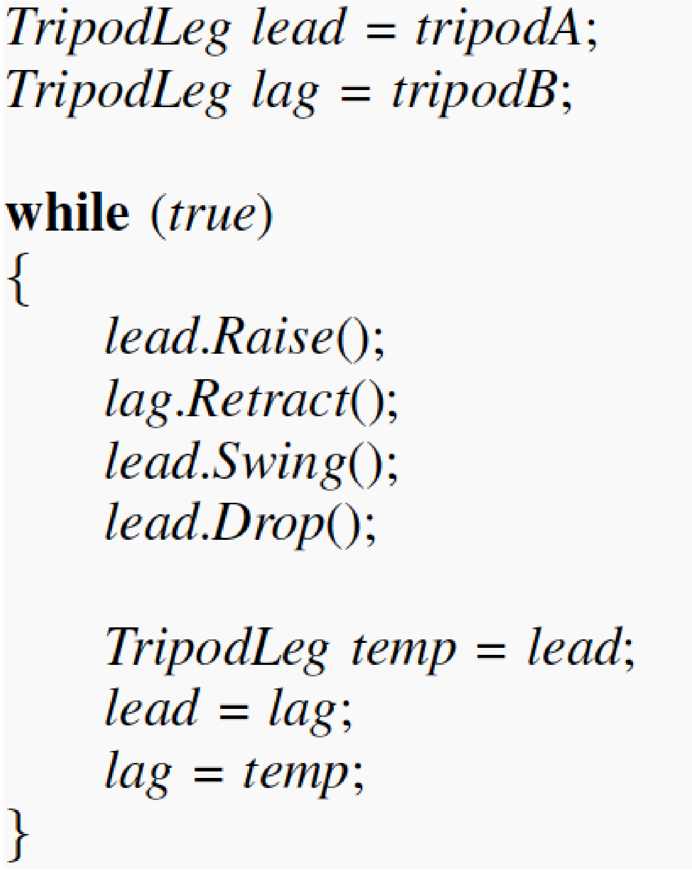
- Begin protraction only if partner legs are down
- Depress legs only if partner legs have retracted
- Begin retraction when partner legs are up

Hexapod coordination rules

R1: Protraction can start only if partner group on ground
R2.1: Protraction starts on completion of retraction
R2.2: Retraction starts on completion of protraction
R3: Retraction can start only when partner group raised
R4: Protraction can end only when partner group retracted

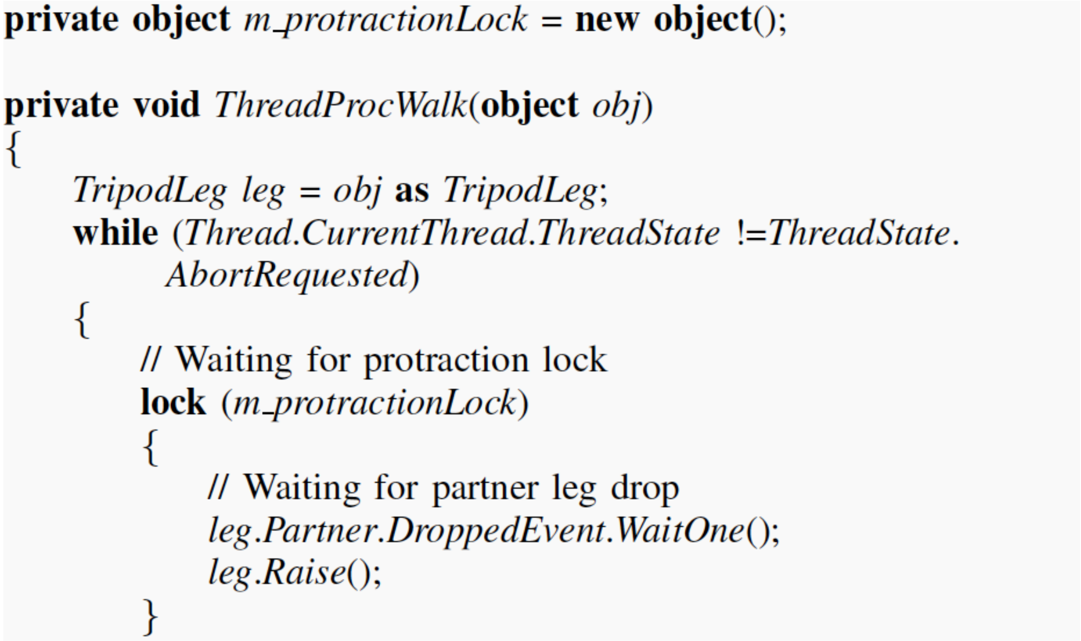
Dürr, Schmitz, Cruse: *Behavior-based modeling of hexapod locomotion: linking biology & technical application*, in *Arthropod Structure & Development*, 2004

Sequential implementation

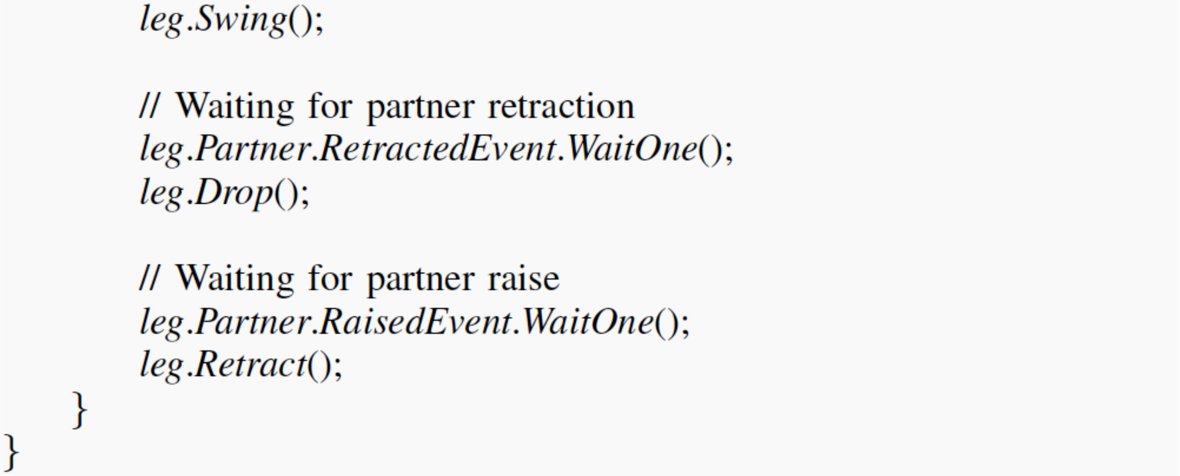


```
TripodLeg lead = tripodA;
TripodLeg lag = tripodB;

while (true)
{
    lead.Raise();
    lag.Retract();
    lead.Swing();
    lead.Drop();

    TripodLeg temp = lead;
    lead = lag;
    lag = temp;
}
```

Multi-threaded implementation

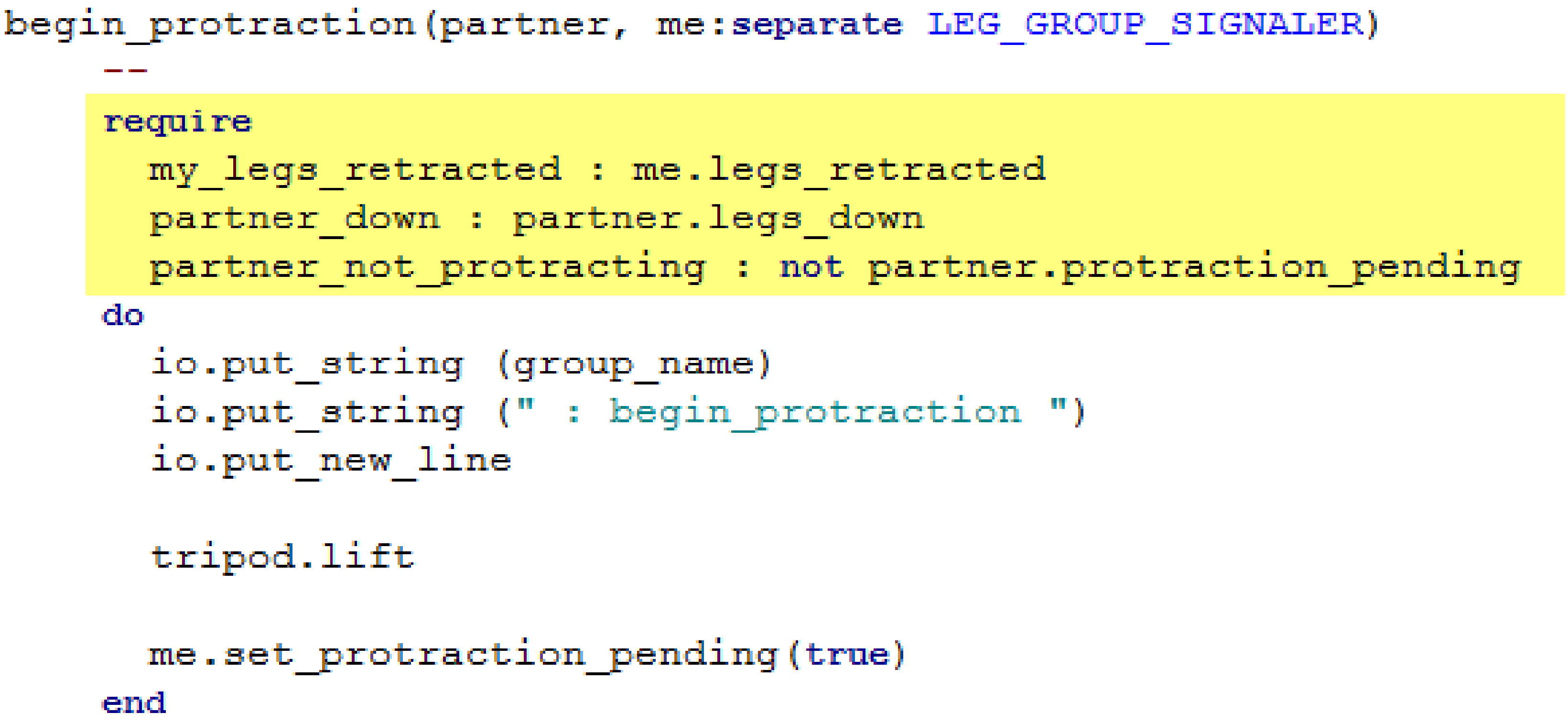


```
private object m_protractionLock = new object();

private void ThreadProcWalk(object obj)
{
    TripodLeg leg = obj as TripodLeg;
    while (Thread.CurrentThread.ThreadState !=ThreadState.
            AbortRequested)
    {
        // Waiting for protraction lock
        lock (m_protractionLock)
        {
            // Waiting for partner leg drop
            leg.Partner.DroppedEvent.WaitOne();
            leg.Raise();
        }
```



```
        leg.Swing();

        // Waiting for partner retraction
        leg.Partner.RetractedEvent.WaitOne();
        leg.Drop();

        // Waiting for partner raise
        leg.Partner.RaisedEvent.WaitOne();
        leg.Retract();
    }
}
```

SCOOP implementation



```
begin_protraction(partner, me:separate LEG_GROUP_SIGNALER)
    --
    require
      my_legs_retracted : me.legs_retracted
      partner_down : partner.legs_down
      partner_not_protracting : not partner.protraction_pending
    do
      io.put_string (group_name)
      io.put_string (" : begin_protraction ")
      io.put_new_line

      tripod.lift

      me.set_protraction_pending(true)
    end
```

Hexapod coordination rules

R1: Protraction can start only if partner group on ground
R2.1: Protraction starts on completion of retraction
R2.2: Retraction starts on completion of protraction
R3: Retraction can start only when partner group raised
R4: Protraction can end only when partner group retracted

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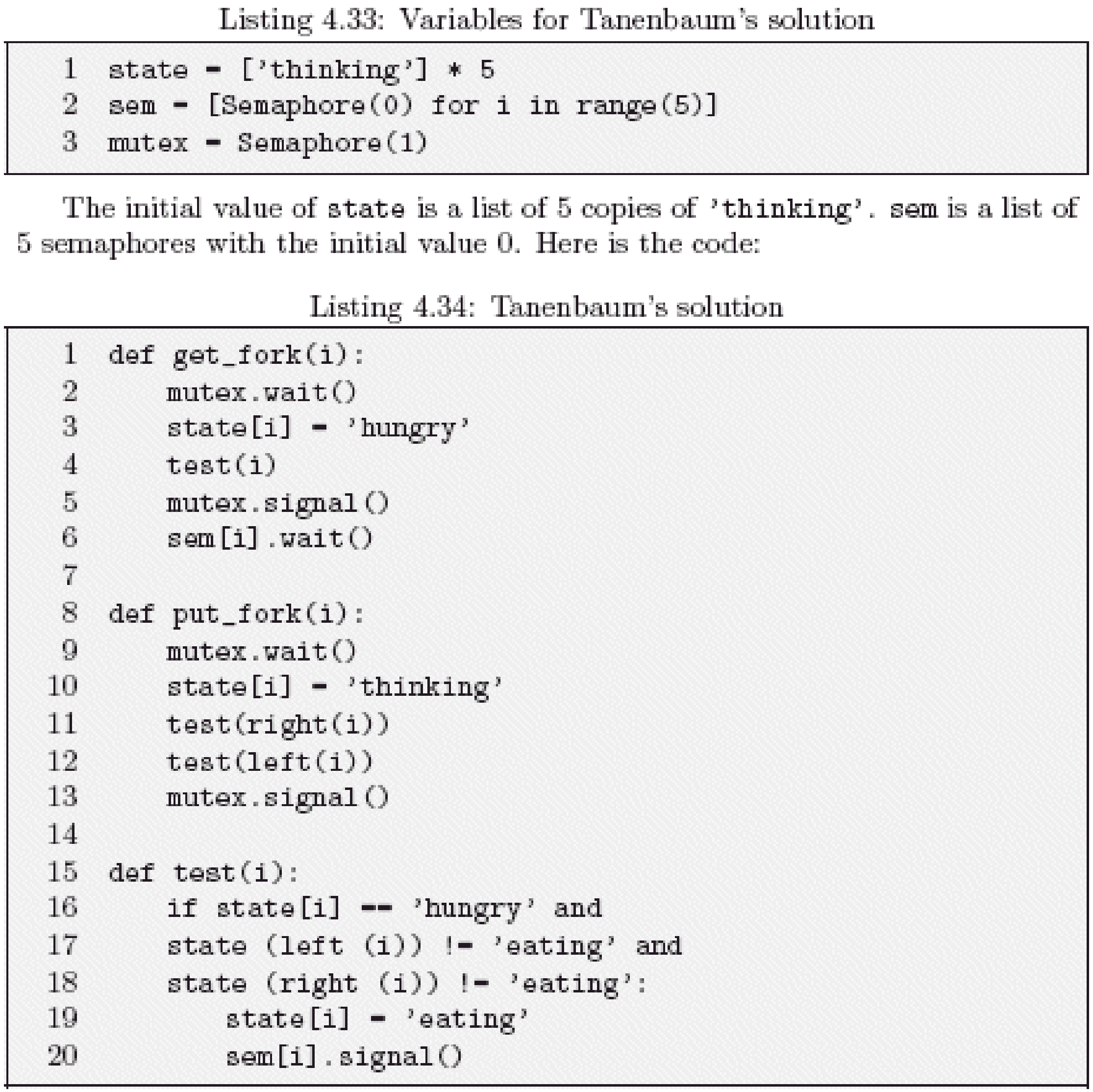
Example 3: dining philosophers



Listing 4.33: Variables for Tanenbaum’s solution

```
state = [’thinking’] * 5
sem = [Semaphore(0) for i in range(5)]
mutex = Semaphore(1)
```

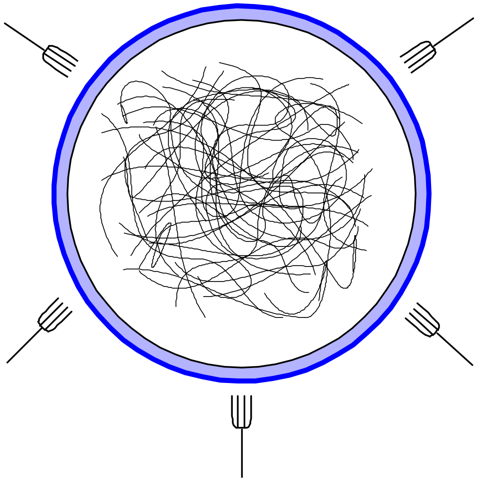
The initial value of `state` is a list of 5 copies of `’thinking’`. `sem` is a list of 5 semaphores with the initial value 0. Here is the code:

Listing 4.34: Tanenbaum’s solution

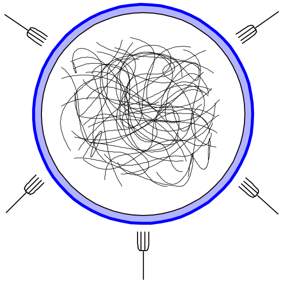
```
def get_fork(i):
    mutex.wait()
    state[i] = ’hungry’
    test(i)
    mutex.signal()
    sem[i].wait()

def put_fork(i):
    mutex.wait()
    state[i] = ’thinking’
    test(right(i))
    test(left(i))
    mutex.signal()

def test(i):
    if state[i] == ’hungry’ and
    state (left (i)) != ’eating’ and
    state (right (i)) != ’eating’:
        state[i] = ’eating’
        sem[i].signal()
```



Dining philosophers in SCOOP (1)

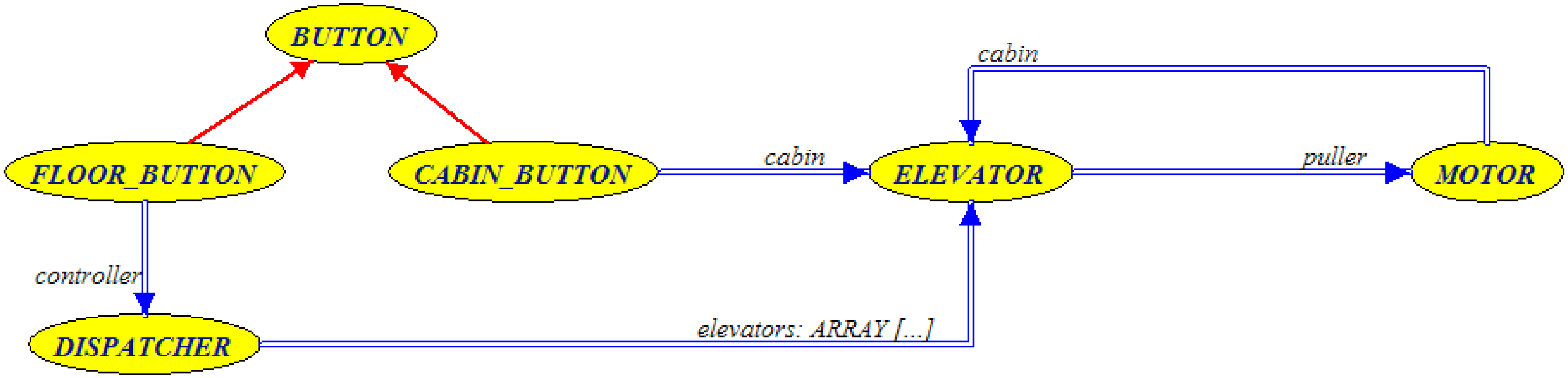


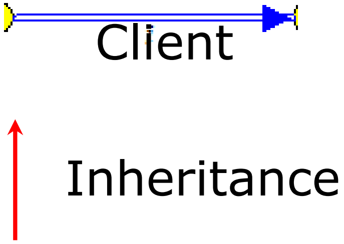
```
class PHILOSOPHER feature
    live
        do
            from getup until over loop
                think ; eat (left, right)
            end
        end

    eat ( l, r: separate FORK )
            -- Eat, having grabbed l and r.
        do ... end

    getup do ... end
    over: BOOLEAN
end
```

Example 4: elevator system





From: *Object-Oriented Software Construction*

For maximal concurrency, all objects are separate

The design of SCOOP (and this presentation)

To achieve the preceding goals, SCOOP makes a number of **restrictions** on the concurrent programming model

This presentation explains and **justifies** these restrictions one after the other

The goal is not to limit programmers but to enable them to **reason** about the programmers

The design of SCOOP

SCOOP intends to make concurrent programming as predictable as sequential programming

A key criterion is "**reasonability**" (not a real word!): the programmer's ability to reason about the execution of programs based only on their text

- *As in sequential O-O programming, with contracts etc.*

SCOOP is not a complete rework of basic programming schemes, but an incremental addition to the basic O-O scheme: **one new keyword**

- **"Concurrency Made Easy"**

Handling concurrency simply

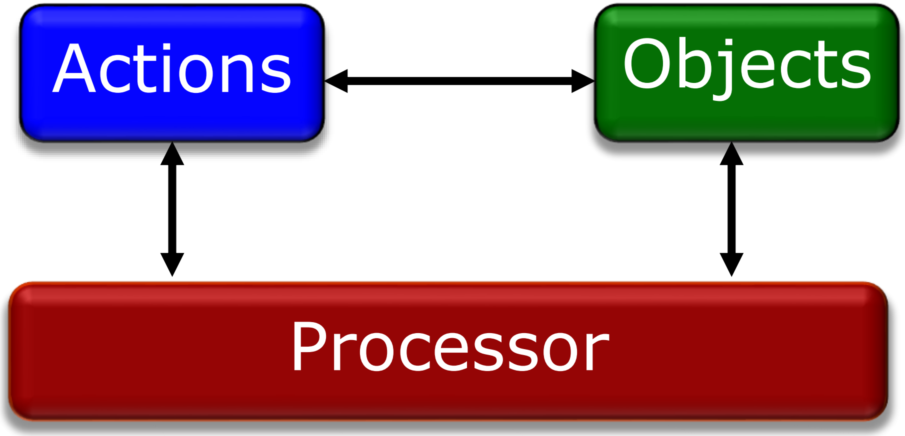
SCOOP narrows down the distinction between sequential & concurrent programming to six properties, studied next:

- **(A)** Single vs multiple "processors"
- **(B)** Regions
- **(C)** Synchronous vs asynchronous calls
- **(D)** Semantics of argument passing
- **(E)** Semantics of resynchronization (lazy wait)
- **(F)** Semantics of preconditions

The starting point **(A)**: processors

To perform a computation is

- To apply certain actions
- To certain objects
- Using certain processors



Sequential: one processor

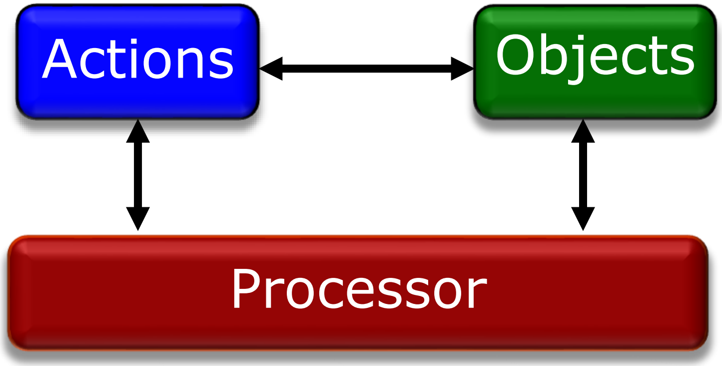
Concurrent: any number of processors

What makes an application concurrent?

Processor:
Thread of control supporting sequential execution of instructions on one or more objects

Can be implemented as:

- Computer CPU
- Process
- Thread
- AppDomain (.NET) …



The SCOOP model is abstract and does not specify the mapping to such actual computational resources

Object-oriented programming

The key operation is “feature call”

```
x.f (args)
```

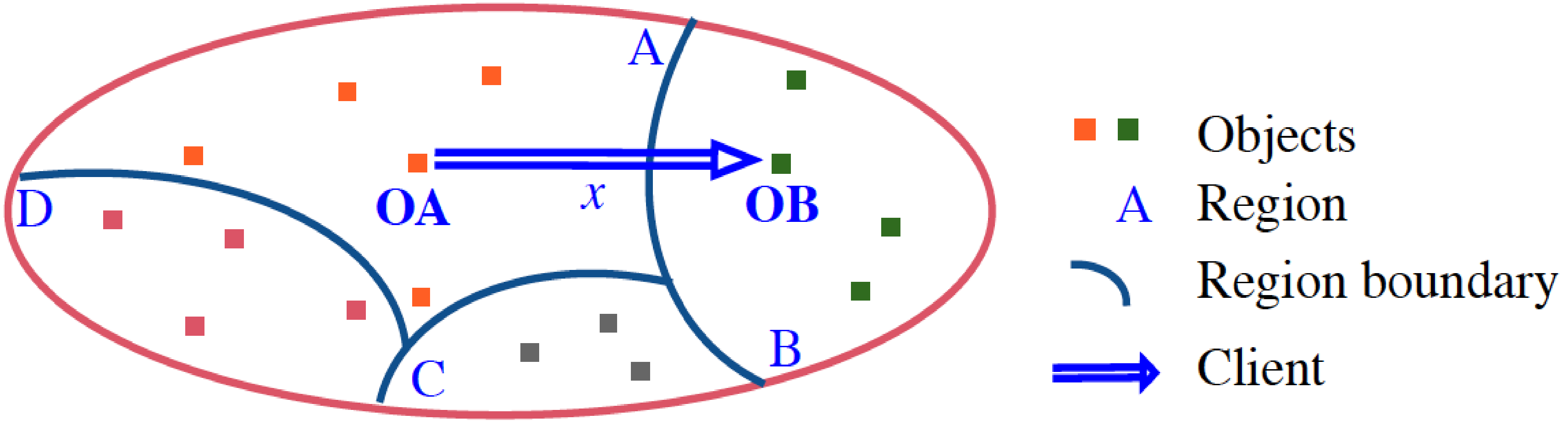
where x, the **target** of the call, denotes an object to which the call will apply the feature f

Which processor is in charge of executing such a call?

(B): Regions

All calls targeting a given object will be executed by a single processor

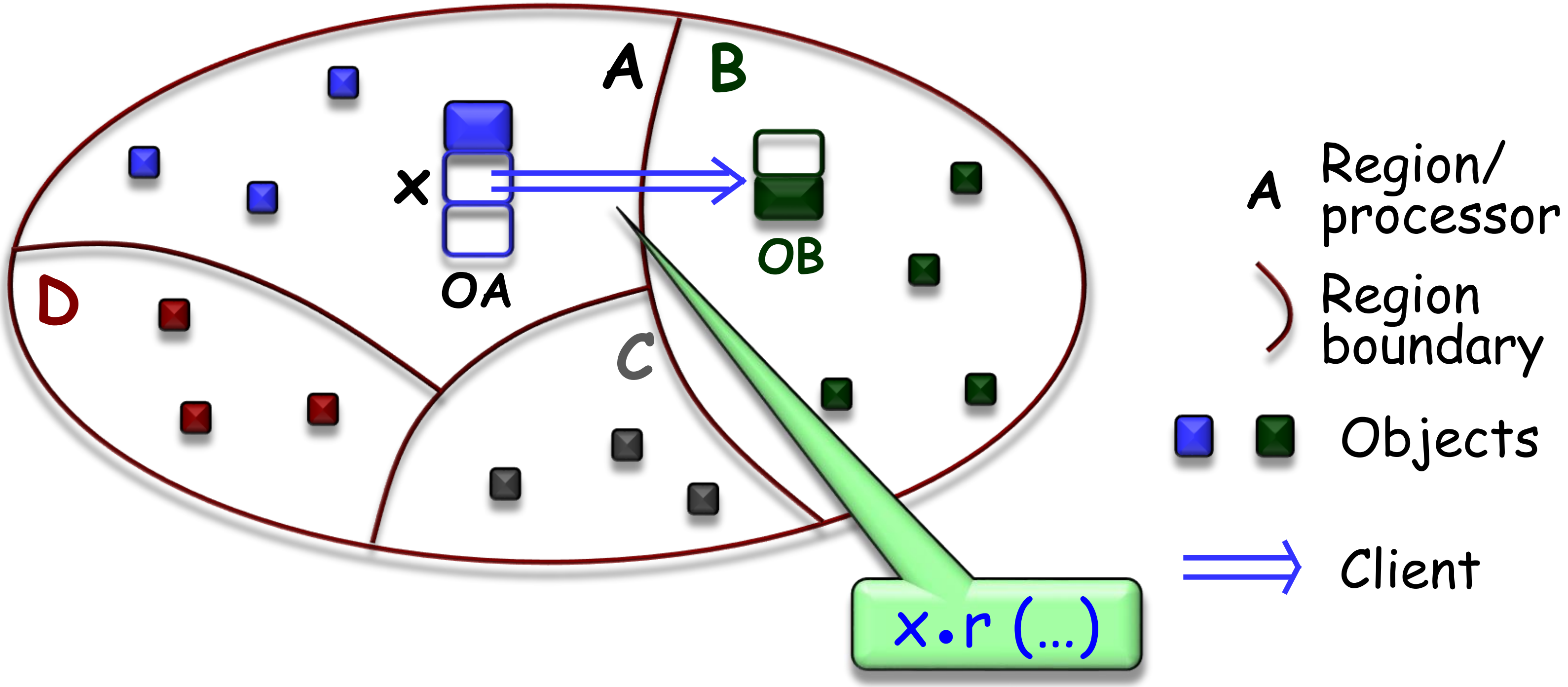
- The set of objects handled by a given processor is called a *region*
- The processor in charge of an object is its *handler*



A consequence: regions

All calls targeting a given object will be executed by a single processor

- The set of objects handled by a given processor is called a *region*



SCOOP restriction: one handler per object

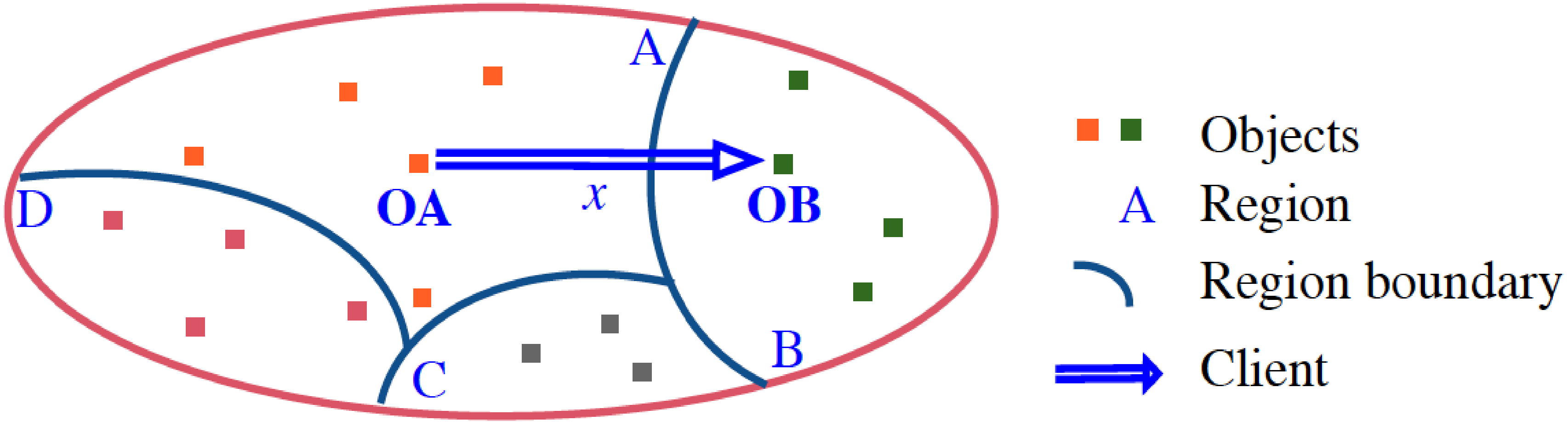
- One processor per object: “handler“

- At most one feature (operation) active on an object at any time

Regions

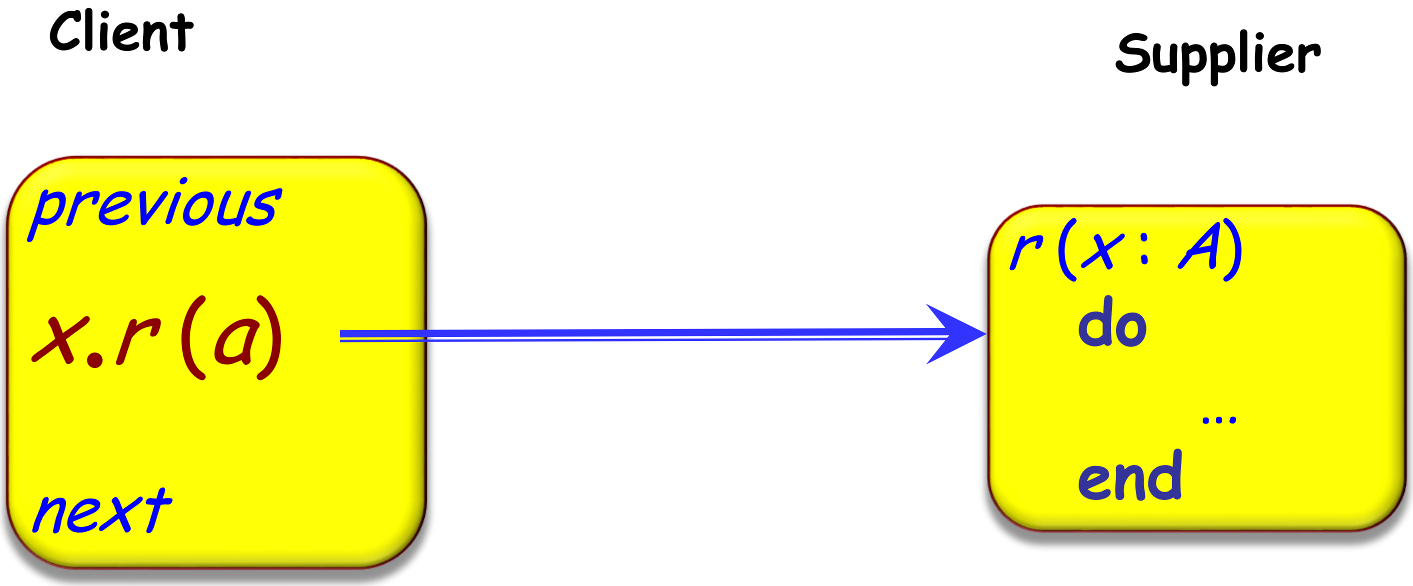
The notion of handler implies a partitioning of the set of objects:

- The set of objects handled by a given processor is called a *region*
- Handler rule implies one-to-one correspondence between processors and regions



(C) The sequential view: O-O feature calls

$$x.r\,(a)$$



Client

Supplier

previous

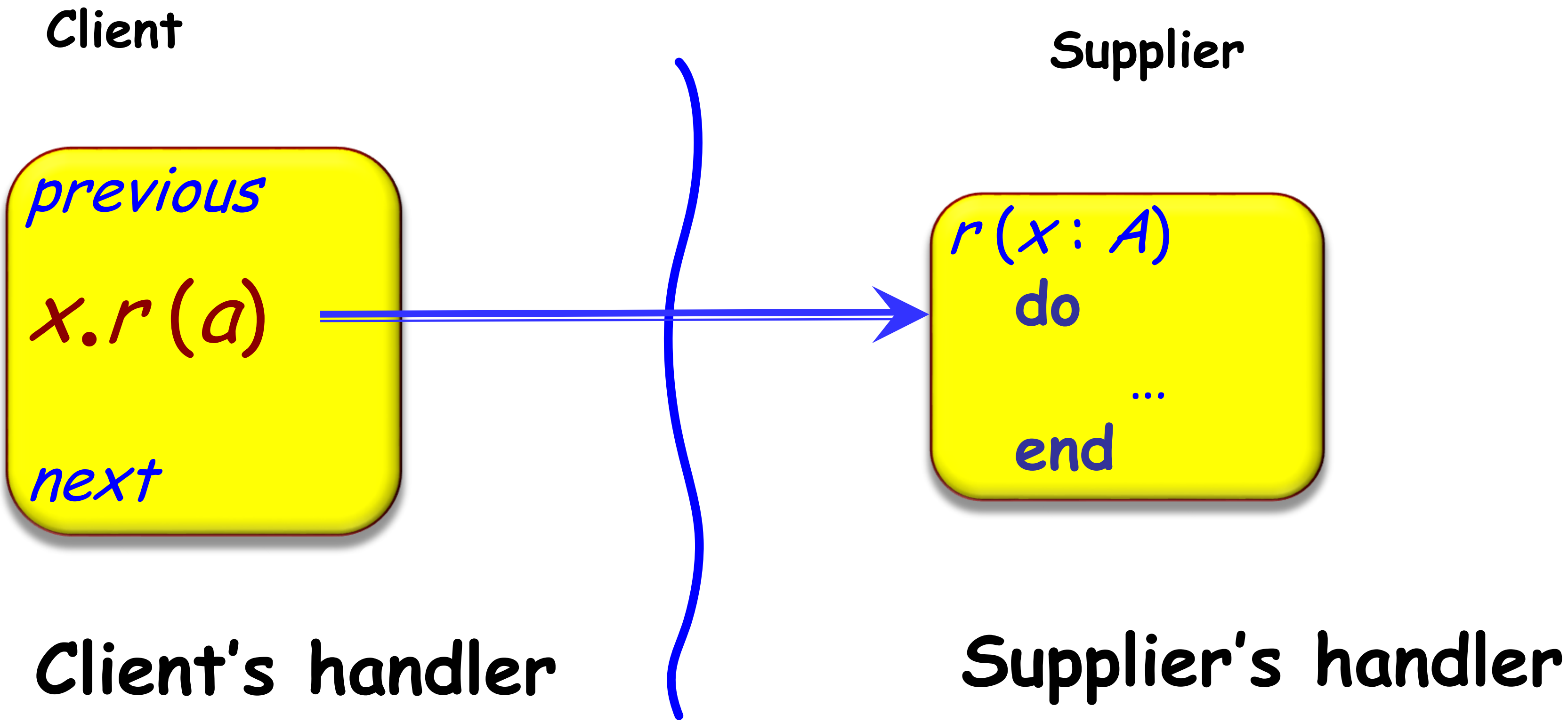
$x.r\,(a)$

next

r (*x* : *A*)
do
...
end

Processor

(C) The concurrent form of call: asynchronous



Client

Supplier

previous

x.r (a)

next

r (x : A)
do
…
end

Client's handler

Supplier's handler

The two forms of O-O call

To wait or not to wait:

  - If same processor, synchronous
  - If different processor, asynchronous

Difference must be captured by syntax:

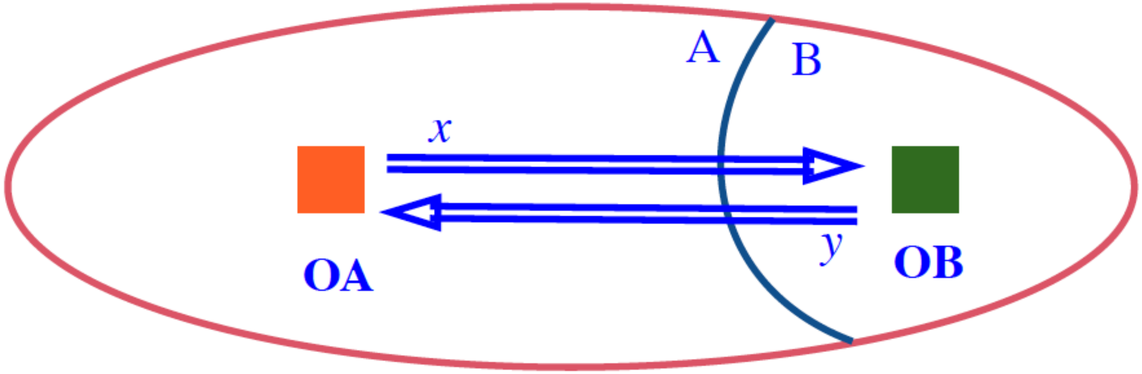
- x: T
- x: **separate** T -- Potentially different processor

Fundamental semantic rule: a call *x.r (a)*

- Waits (i.e. is synchronous) for non-separate *x*
- Does not wait (is asynchronous) for separate *x*

Why *potentially* separate?

separate declaration only states that the object *might* be handled by a different processor



- In class A: *x*: **separate** *B*
- In class B: y: **separate** *A*
- In A, what is the type of x.y?

In some execution, the value might be a reference to an object in the current region

Call vs application

With asynchrony we must distinguish between **feature call** and **feature application**

The execution

`x . r (...)`

is the **call**, and (with x separate) will not wait (the client just logs the call)

The execution of r happens later and is called the feature **application**

Consistency rules: avoiding traitors

```
nonsep: T

sep: separate T

nonsep := sep

nonsep.p (a)
```

Traitor!

More traitor protection through the type system!

(D) Access control policy

Since separate calls are asynchronous there is a real danger of confusion

Consider for example

```
remote_stack : separate STACK [T]
...
remote_stack.put (a)
... Instructions not affecting the stack...
y := my_stack.item
```

(D) Access control policy

SCOOP requires the target of a separate call to be a **formal argument** of enclosing routine:

```
put (s: separate STACK [T]; value : T)
        -- Store value into s.
    do
        s.put (value)
    end
```

To use separate object:

```
my_stack: separate STACK [INTEGER]
create my_stack
put (my_stack, 10)
```

(D) Separate argument rule

The target of a separate call
must be an argument of the enclosing routine

Separate call: *x*.*f* (...) where *x* is separate

(D) Wait rule

A routine call guarantees exclusive access to the handlers (the processors) of all separate arguments

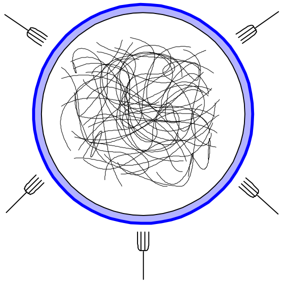
a_routine (*nonsep_a*, *nonsep_b*, *sep_c*, *sep_d*, *sep_e*)

Exclusive access to *sep_c*, *sep_d*, *sep_e* within *a_routine*

An example: from sequential to concurrent

```
transfer (source, target: separate ACCOUNT;
            amount: INTEGER)
        -- Transfer amount, if available, from source to target.
    do
        if source.balance >= amount then
            source.withdraw  (amount)
            target.deposit   (amount)
        end
    end
```

Dining philosophers in SCOOP (1)



```
class PHILOSOPHER feature
        live
                do
                        from getup until over loop
                                think ;  eat (left, right)
                        end
                end

        eat ( l, r: separate FORK )
                        -- Eat, having grabbed l and r.
                do ... end

        getup do ... end
        over: BOOLEAN
end
```

(D) What the wait rule means

Beat enemy number one in concurrent world: atomicity violations

- Data races
- Illegal interleaving of calls

Data races cannot occur in SCOOP

(D) Wait rule

A routine call guarantees exclusive access to the handlers (the processors) of all separate arguments

a_routine (nonsep_a, nonsep_b, sep_c, sep_d, sep_e)

Exclusive access to *sep_c, sep_d, sep_e* within *a_routine*

Semantics vs implementation

Older SCOOP literature says that feature application "waits" until all the separate arguments' handlers are available

This is not necessary!

What matters is **exclusive access**: implementation does not have to wait unless semantically necessary

The implementation performs some of these optimizations

```
f (a, b, c: separate T)
        do
                something_else
                a.r
                b.s
        end
```

No need to wait for a and b until here

No need to wait for c!

(E) Resynchronization: lazy wait

How do we resynchronize after asynchronous (separate) call?
No explicit mechanism!

The client will wait when, and only when, it needs to:

```
x.f
x.g (a)
y.f
…
value := x.some_query
```

Wait here!

Lazy wait (also known as wait by necessity)

(E) Synchrony vs asynchrony revisited

For a separate target *x*:

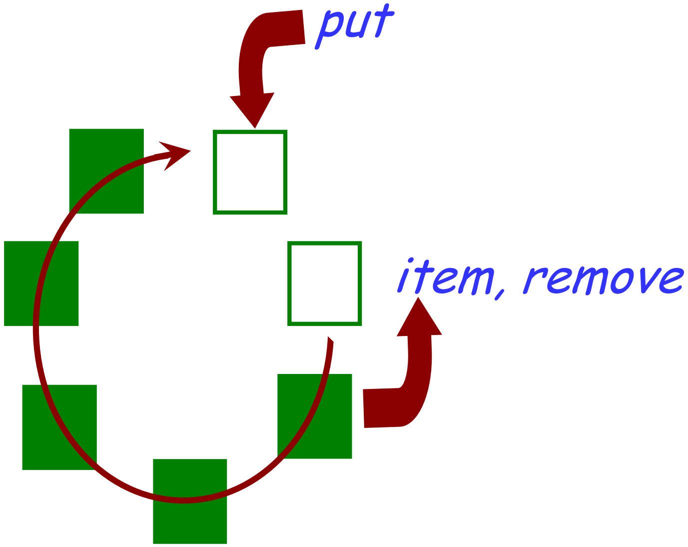
- *x*. *command* (...) is asynchronous
- *v* := *x*. *query* (...) is synchronous

Exercise

If we do want to resynchronize explicitly, what do we do?

(F) Contracts

What becomes of contracts, in particular preconditions, in a concurrent context?



```
put (b: BUFFER [G ]; v: G )
        -- Store v into b.
  require
        not b.is_full
  do
        ...
  ensure
        not b.is_empty
  end
```

```
my_queue : BUFFER [T ]
...

if not my_queue.is_full then
```

```
        put (my_queue, t )
end
```

(F) Contracts

```
put (b: separate QUEUE [INTEGER ] ; v: INTEGER)
            -- Store v into b.
        require
            not b.is_full
            v > 0
        do
            b.put (v)
        ensure
            not b.is_empty
        end

...
put (my_buffer, 10 )
```

(F) Contracts

```
put (b: BUFFER [INTEGER ] ; i : INTEGER)
                -- Store i into buffer.
        require
                not b.is_full
                i > 0
        do
                b.put (i)
        ensure
                not b.is_empty
        end

...
put (my_buffer, 10 )
```

Precondition becomes **wait condition**

Bank transfer (version with contracts)

```
transfer (source, target: separate ACCOUNT;
              amount: INTEGER)
        -- Transfer amount from source to target.
    require
           source.balance >= amount
    do
          source.withdraw  (amount)
          target.deposit     (amount)
    ensure
          source.balance = old source.balance – amount
          target.balance = old target.balance + amount
    end
```

(F) Full synchronization rule

A call with separate arguments waits until:

- The corresponding objects are all available
- Preconditions hold

"Separate call":

x.f (a) -- where *a* is separate

Which semantics applies?

```
put (buf : separate BUFFER [INTEGER]; i : INTEGER)
        require
                not buf.is_full
                i > 0
        do
                 buf.put (i)
         end
```

Wait condition

Correctness condition

```
my_buffer : separate BUFFER [INTEGER]
put (my_buffer, 10)
```

Generalized semantics of preconditions

The different semantics is surprising at first:

  - Separate: wait condition
  - Non-separate: correctness condition

At a high abstraction level, however, we may consider that

- Wait semantics always applies in principle
- Sequentiality is a special case of concurrency
- Wait semantics boils down to correctness semantics for non-separate preconditions.
    - Smart compiler can detect some cases
    - Other cases detected at run time