Robotics Programming Laboratory

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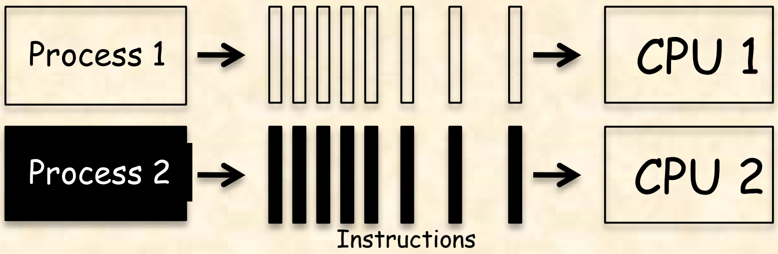
Lecture 4:

Introduction to concurrency and SCOOP

Multiprocessing, parallelism*

Many of today's computations can take advantage of multiple processing units (through *multi-core* processors):



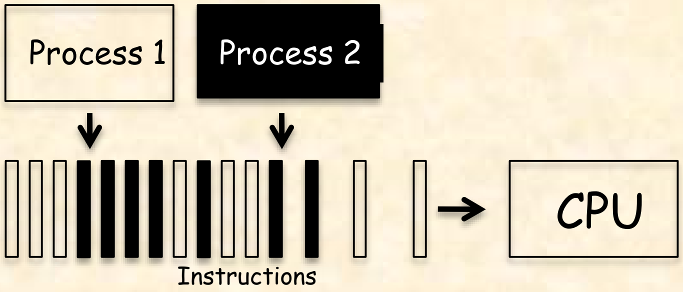
* This slide and the next are from material developed by Sebastian Nanz as part of a jointly taught ETH cours

Terminology:

- **Multiprocessing** : the use of more than one processing unit in a system
- **Parallel execution**: processes running at the same time

Multitasking, concurrency

Even on systems with a single processing unit we may give the illusion of that several programs run at once



The OS switches between executing different tasks

Terminology:

- **Interleaving**: several tasks active, only one running at a time
- **Multitasking**: the OS runs interleaved executions
- **Concurrency**: multiprocessing, multitasking, or any combination

Reasons for using concurrency

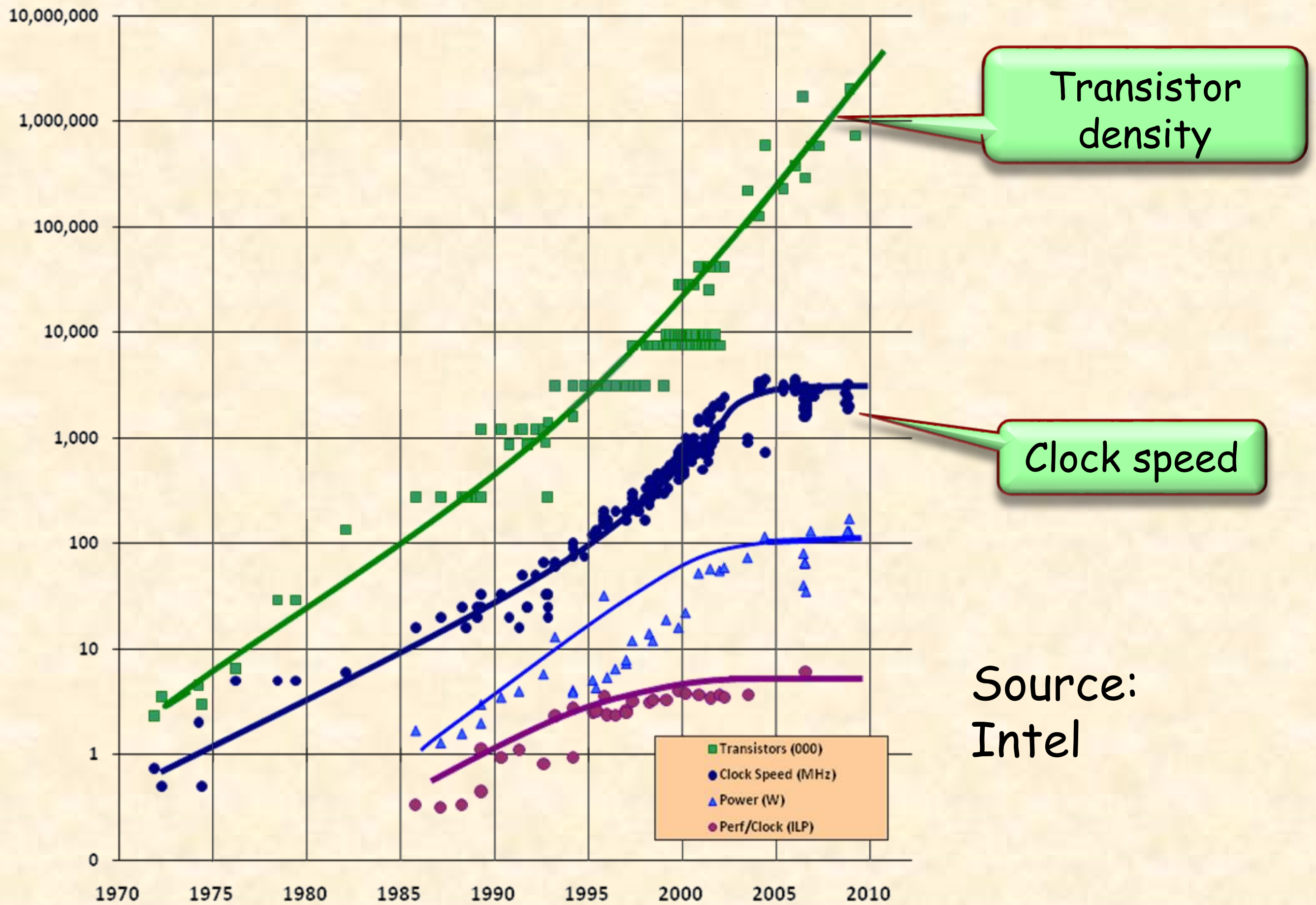
1. Performance
2. Convenience
3. Modeling

Faster computation through multiprocessing

Programs performing several actions at once (through multithreading)

Adapting to the world's built-in concurrency (networking, real-time, robotics, modeling)

The end of Moore's Law as we knew it



Source: Intel

What they say about concurrent programming

Intel, 2006:

- *Multi-core processing is taking the industry on a fast-moving and exciting ride into profoundly new territory*

Rick Rashid, head of Microsoft Research, 2007:

- *Multicore processors represent one of the largest technology transitions in the computing industry today, with deep implications for how we develop software*

Bill Gates:

- *We have never had a problem like this.*
  A breakthrough is needed.

Dave Patterson, UC Berkeley, 2007:

- *Industry has basically thrown a Hail Mary. The whole industry is betting on parallel computing. They've thrown it, but the big problem is catching it*

US National Academy of Science, 2011

Heroic programmers *can exploit vast amounts of parallelism…*

However, ***none of those developments comes close to the ubiquitous support for programming parallel hardware*** *that is required to ensure that IT's effect on society over the next two decades will be as stunning as it has been over the last half-century*

Programming for heroes: dining philosophers

Listing 4.33: Variables for Tanenbaum's solution

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

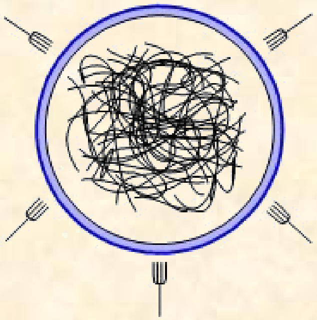
The initial value of state is a list of 5 copies of 'thinking'. sem is a list of 5 semaphores with the initial value 0. Here is the code:

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()
```



Allen Downey: The Little Green Book of Semaphores, greenteapress.com/semaphores/

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```

Bank transfer

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

	Jane	Jill	Joan
	100	0	100
transfer (*Jane*, *Jill*, 100) 1	0	100	0
transfer (*Jane*, *Joan*, 100) 2	-100	0	100

Bank transfer (better version)

```
transfer (source, target:                  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
```

The inability to reason from APIs

if acc1.balance >= 100  **hen** transfer (acc1, **acc2**, 100) **end**

if acc1.balance >= 100 **hen** transfer (acc1, **acc3**, 100) **end**

```
invariant
        balance >= 0
```

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

The core question

Can we bring concurrent programming
to the same level
of **abstraction** and **convenience**
as sequential programming?

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 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

Notation adapted from Mordechai Ben Ari,
Principles of Concurrent and Distributed Programming

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

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

Priority inversion

Norm: normal customer

Frieda: member of “Friends of Ecstatic”: priority over Norm

Ben: benefactor (priority over both)

Bookings open at 9; Ben comes at 9:02, jumps to front of line

Cashier, handling Norm’s request, pushes Norm aside to take care of Ben; but Ben uses a credit card and the card machine is in use to check Norm’s card. So Ben, despite his elite status, has to wait.

In walks Frieda, ready to pay cash

Cashier interrupts Norm’s transaction again (card machine remains busy) and gets Frieda a ticket

Norm’s transaction resumes and, as soon as credit check finishes, is interrupted for Ben — too late, as Frieda walked away with the last ticket

Priority inversion: scenario

Time	Active participant	Request or action	Answer or result	Available seats
9:00	Theatre	*Theater opens*		1
9:01	*Norm*	*Try to book*	Start card check	1
9:02	*Ben*	*Interrupt Norm*	**Success**	1
9:03	*Ben*	*Try to book*	Card machine busy: wait	1
9:04	*Norm*	*Resume transaction*	Resume card check	1
9:05	*Frieda*	*Interrupt Norm*	**Success**	1
9:06	*Frieda*	*Try to book*	**Success** *(last ticket)*	0
9:07	*Norm*	*Finish card check*	Card went through (or not)	0
9:08	*Ben*	*Interrupt Norm*	**Success**	0
9:09	*Ben*	*Try to book*	**Failure**! All seats gone	0

Choices in the SCOOP model

Choice 1: object-oriented programming

- (Static) type and module structure: class
- (Dynamic) data structure: object
- Inheritance for (static) reuse and (dynamic) binding

Choice 2: processors

Computation is the responsibility of "processors", each of which is a sequential execution mechanism

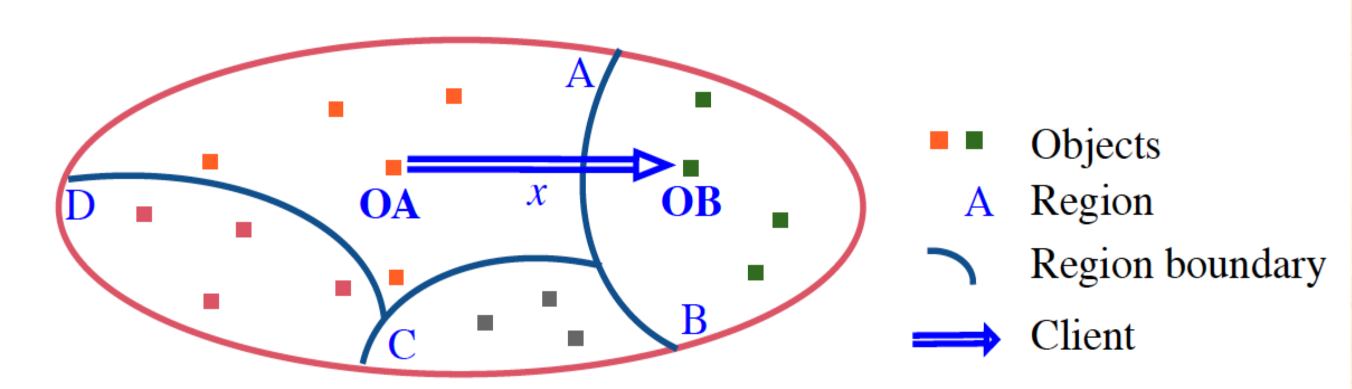
(such as a thread)

Choice 3: regions

Objects partitioned into regions

Operations on object in a given region are the responsibility of á processor, the region's handler

Some regions, however, are passive: they do not have a handler



Consequence of choice 3

At any given time, at most one operation in progress on any given object

(In fact, on objects in any given region)

No intra-object concurrency

Choice 4

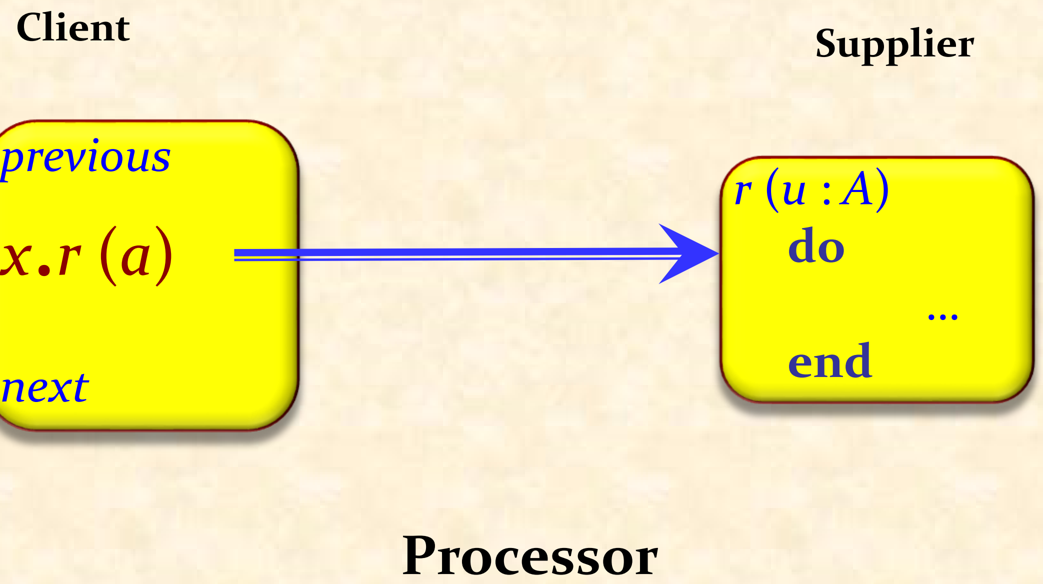
The execution of a call requested by a processor on objects in another region is asynchronous

Introduce distinction between:

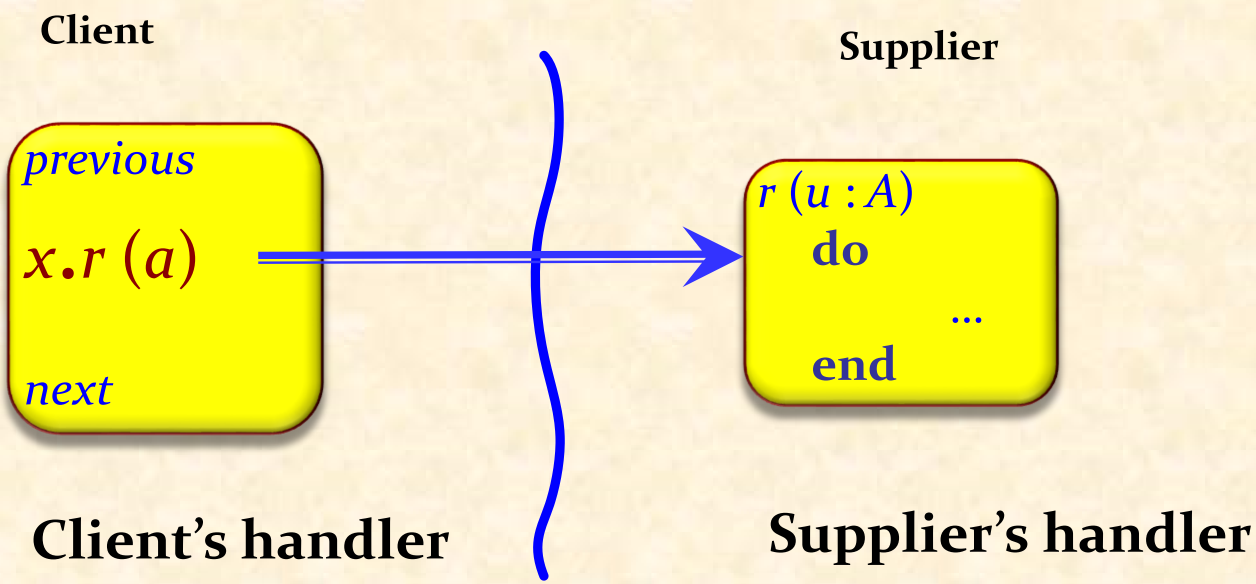
- Routine/method **call**
- Routine **application**

The sequential view: O-O feature calls

$$x.r\ (a)$$



The concurrent form of call: asynchronous



Choice 5

The application of a call has exclusive access to the needed object

Choice 6

The application of a call has exclusive access to the needed **objects**

Choice 7

A query is blocking (synchronous)

Based on distinction between two kinds of operation:

- **Command**: does something
  (in programming languages: procedures)
- **Query**: gives some information
  (in programming languages: functions, fields/attributes/instance variables)

Choice 6

The application of a call has exclusive access to the needed **objects**

Exclusive access to multiple objects

```
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
```

Choice 8

An operation on an object may have to wait until a condition is satisfied (expressed by a precondition)

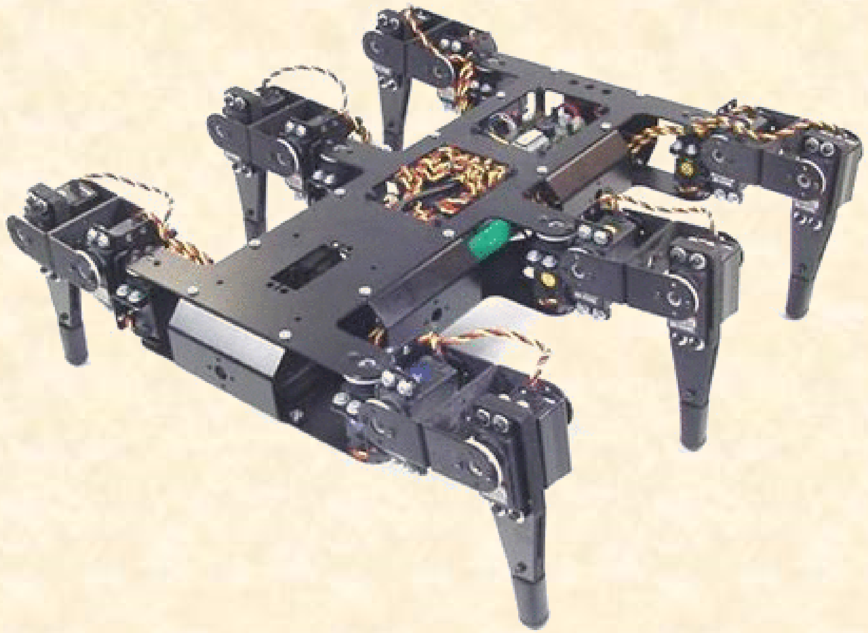
Using preconditions for waiting

if acc1.balance >= 100 **then** transfer (acc1, **acc2**, 100) **end**

if acc1.balance >= 100 **then** transfer (acc1, **acc3**, 100) **end**

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

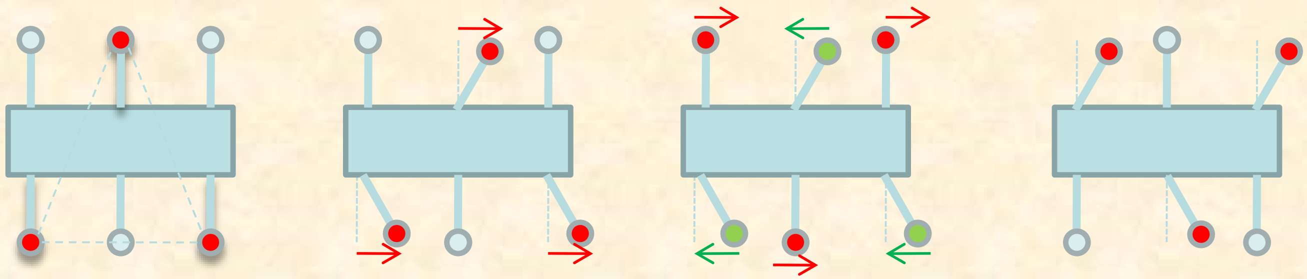
Hexapod robot



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 version

```
begin_protraction (partner, me: separate LEG_GROUP)

    require
        me.legs_retracted
        partner.legs_down
        not partner.protraction_pending

    do
        tripod.lift
        me.set_protraction_pending
    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

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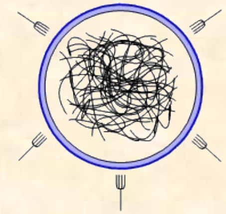
Using preconditions for exclusive access

```
transfer (source, target: separate ACCOUNT;
        amount: INTEGER)
    -- If enough funds, transfer amount 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)

Dining philosophers



```
class PHILOSOPHER create make feature
    left, right: separate FORK
    make (u, v: separate FORK)     do left:= u ; right := v end
    live
        do
            from until False loop
                think ; eat (left, right)
            end
        end

    eat (l, r: separate FORK) do left.pick  ;  right.pick ; ... end

    think do ... end
end
```

```
require
    l.picked
    r.picked
```

To know more

SCOOP pages at

- http://cme.ethz.ch/scoop/
- https://www.eiffel.org/doc/solutions/Concurrent%20Eiffel%20with%20SCOOP