Some occam-π Basics

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Co631 (Concurrency)

Some occam-π Basics

Communicating processes ...

A flavour of occam-π …

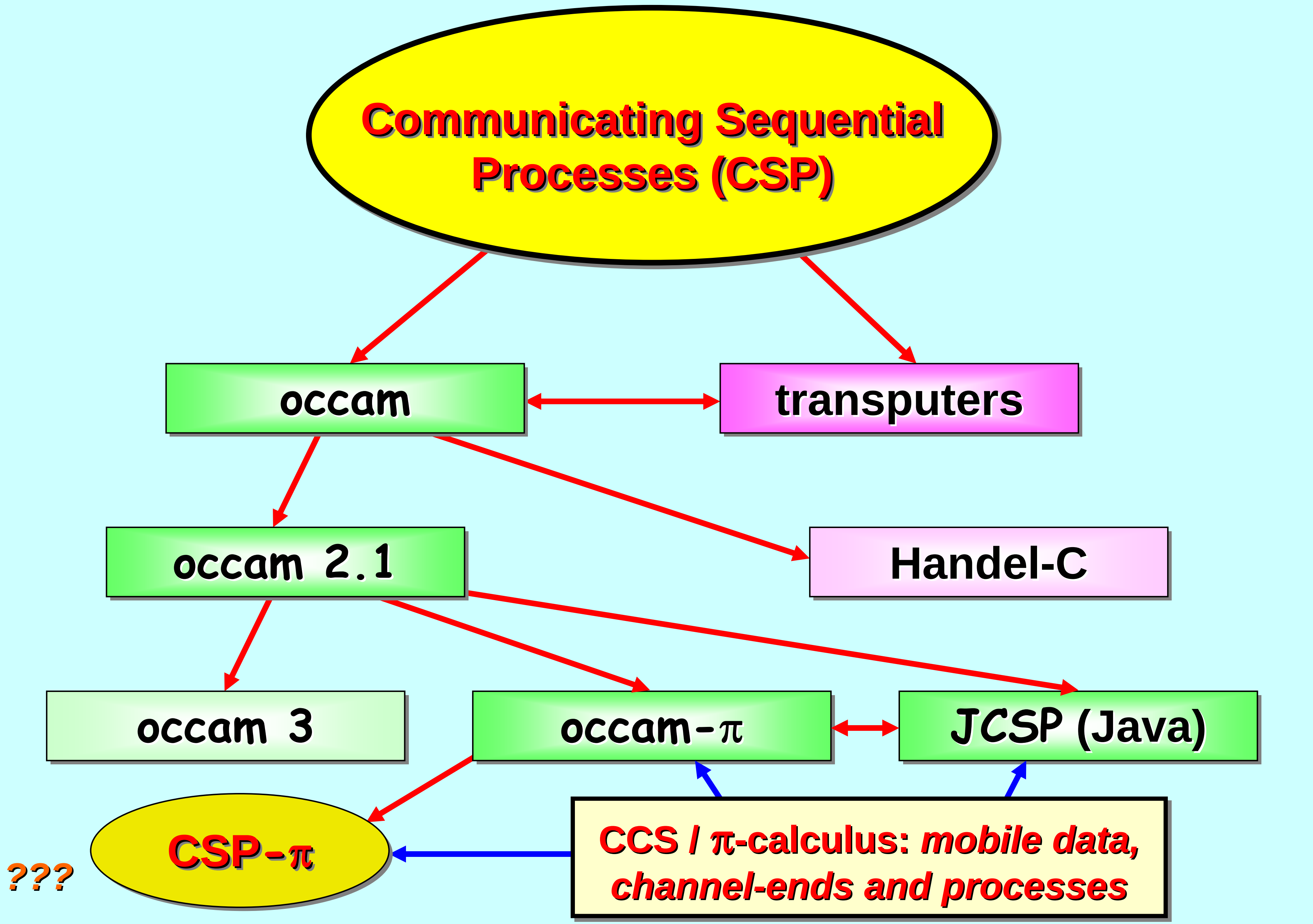
Networks and communication …

Types, channels, processes …

Primitive processes …

Structured processes …

‘Legoland’ …



Communicating Sequential Processes (CSP)
occam
transputers
occam 2.1
Handel-C
occam 3
occam-π
JCSP (Java)
CSP-π
???
CCS / π-calculus: mobile data, channel-ends and processes

Communicating Sequential Processes (CSP)

A mathematical theory for specifying and verifying complex patterns of behaviour arising from interactions between concurrent objects.

CSP has a formal, and ***compositional***, semantics that is in line with our informal intuition about the way things work.

Claim

Why CSP?

- Encapsulates fundamental principles of communication.
- Semantically defined in terms of structured mathematical model.
- Sufficiently expressive to enable reasoning about deadlock and livelock.
- Abstraction and refinement central to underlying theory.
- Robust ***and commercially supported*** software engineering tools exist for formal verification.

Why CSP?

- **CSP** libraries available for Java (**JCSP, CTJ**).

- Ultra-lightweight kernels* have been developed yielding ***sub-microsecond*** overheads for context switching, process startup/shutdown, synchronized channel communication and high-level shared-memory locks.

- Easy to learn and easy to apply …

* not yet available for JVMs (or Core JVMs!)

Why CSP?

- After 5 hours teaching:
  - exercises with 20-30 threads of control
  - regular and irregular interactions
  - appreciating and eliminating race hazards, deadlock, etc.

- **CSP** is (parallel) architecture neutral:
  - message-passing
  - shared-memory

So, what is CSP?

CSP deals with ***processes***, ***networks*** of processes and various forms of ***synchronisation*** / ***communication*** between processes.

A network of processes is also a process - so **CSP** naturally accommodates layered network structures (***networks of networks***).

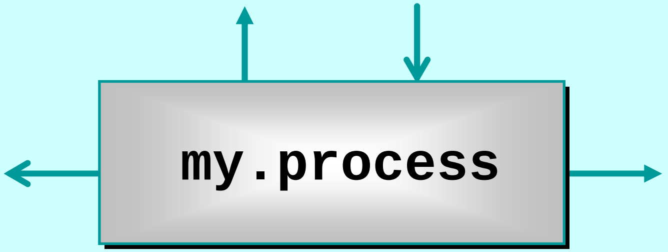
We do not need to be mathematically sophisticated to work with **CSP**. That sophistication is pre-engineered into the model. We benefit from this simply by using it.

Processes

`my.process`

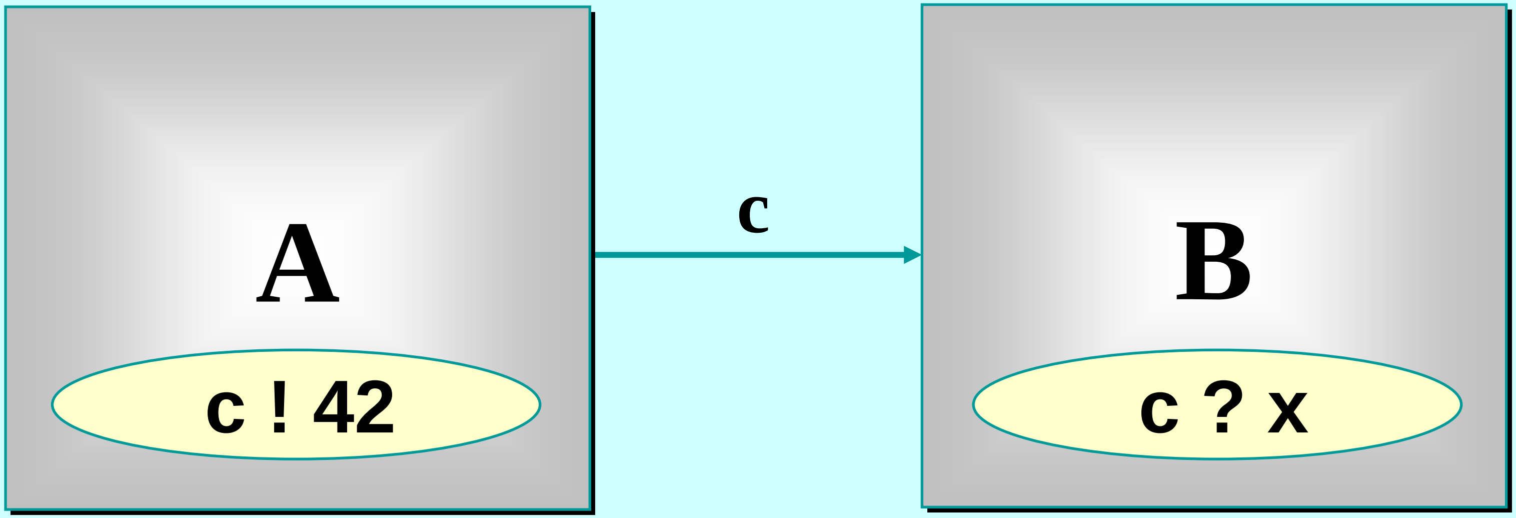
- A **process** is a component that encapsulates some data structures and algorithms for manipulating that data.
- Both its data and algorithms are **private**. The outside world can neither see that data nor execute those algorithms! [They are not *objects*.]
- The algorithms are executed by the process in its own thread (or threads) of control.
- So, how does one process interact with another?

Processes



- The simplest form of interaction is *synchronised* message-passing along ***channels***.
- The simplest forms of channel are ***zero-buffered*** and ***point-to-point*** (i.e. *wires*).
- But, we can have ***buffered*** channels (*blocking*/*overwriting*).
- And ***any-1***, ***1-any*** and ***any-any*** channels.
- And structured multi-way synchronisation (e.g. ***barriers***) …
- And high-level (e.g. **CREW**) *shared-memory* locks …

Synchronised Communication

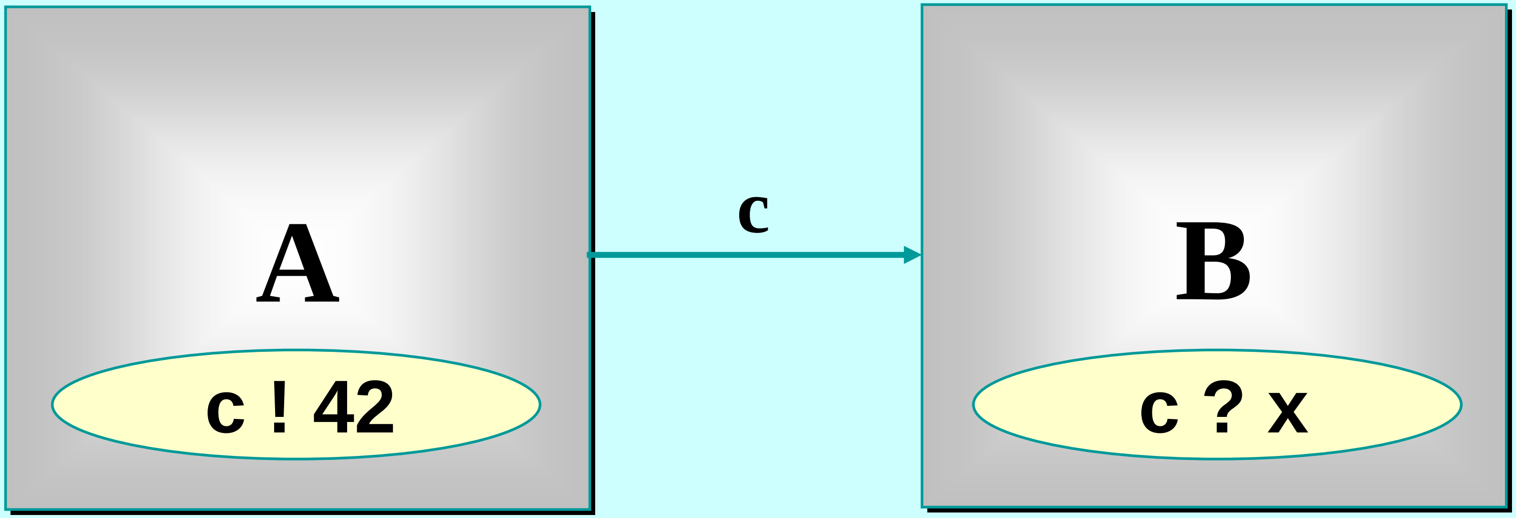


A may ***write*** on ***c*** at any time, but has to wait for a ***read***.

B may ***read*** from ***c*** at any time, but has to wait for a ***write***.

(A (c) || B (c)) \ {c}

Synchronised Communication



Only when both ***A*** and ***B*** are ready can the communication proceed over the channel ***c***.

(A (c) || B (c)) \ {c}

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occam-π: Aspirations and Principles

- Simplicity
  - There must be a consistent (*denotational*) semantics that matches our intuitive understanding for *Communicating Mobile Processes*.
  - There must be as direct a relationship as possible between the formal theory and the implementation technologies to be used.
  - Without the above link (*e.g. using C++/pthreads or Java/monitors*), there will be too much uncertainty as to how well the systems we build correspond to the theoretical design.
- Dynamics
  - Theory and practice must be flexible enough to cope with process mobility, location awareness, network growth and decay, disconnect and re-connect and resource sharing.
- Performance
  - Computational overheads for managing (*millions of*) evolving processes must be sufficiently low so as not to be a show-stopper.
- Safety
  - Massive concurrency – but no race hazards, deadlock, livelock or process starvation.

occam-π

- Process, communication, networks (**PAR**)
- Choice between multiple events (**ALT**)
- Mobile data types
- Mobile channel types
- Mobile process types
- Performance

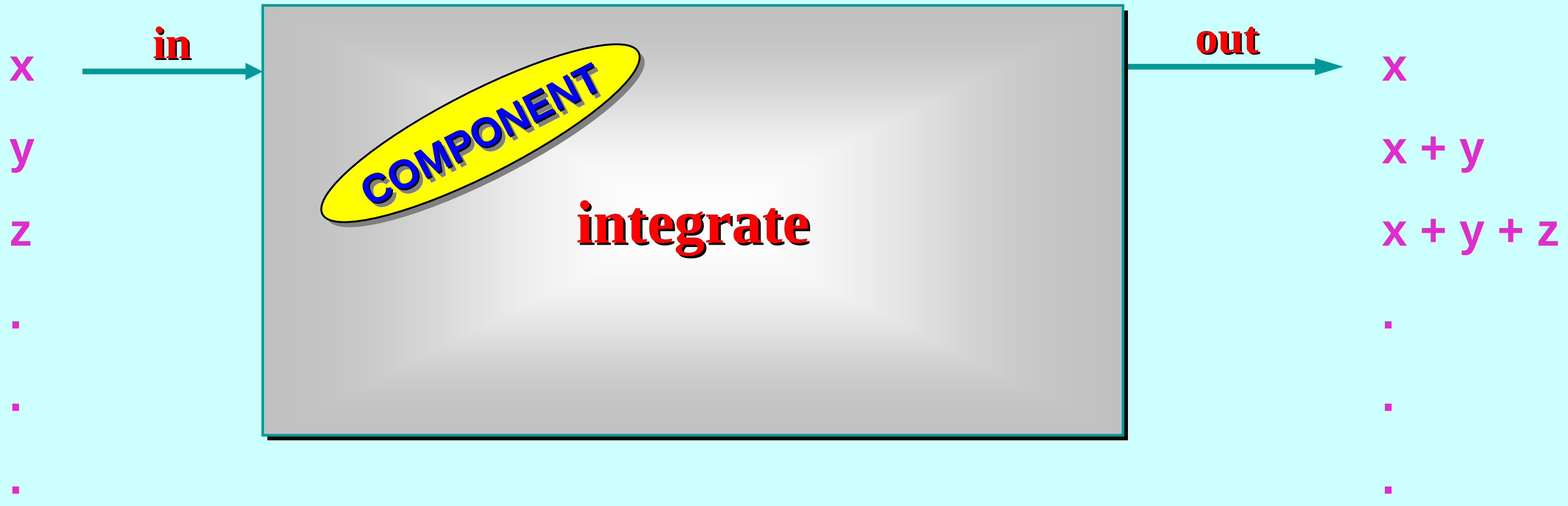
+ shared channels,
channel bundles, alias checking, no race hazards,
dynamic memory, recursion, forking, no garbage,
protocol inheritance, extended rendezvous, process priorities, …

Processes and Channel-*Ends*


```
PROC integrate (CHAN INT in?, out!)
```

An **occam** process may only use a channel parameter *one-way* (either for input or for output). That direction is specified (`?` or `!`), along with the structure of the messages carried – in this case, simple `INT`s. The compiler checks that channel usage within the body of the `PROC` conforms to its declared direction.

Processes and Channel-*Ends*




```
PROC integrate (CHAN INT in?, out!)
  INITIAL INT total IS 0:
  WHILE TRUE
    INT x:
    SEQ
      in ? x
      total := total + x
      out ! total
:
```

serial implementation

With an Added Kill Channel


```
PROC integrate.kill (CHAN INT in?, out!, kill?)
  INITIAL INT total IS 0:
  INITIAL BOOL ok IS TRUE:
  ...  main loop
:
```

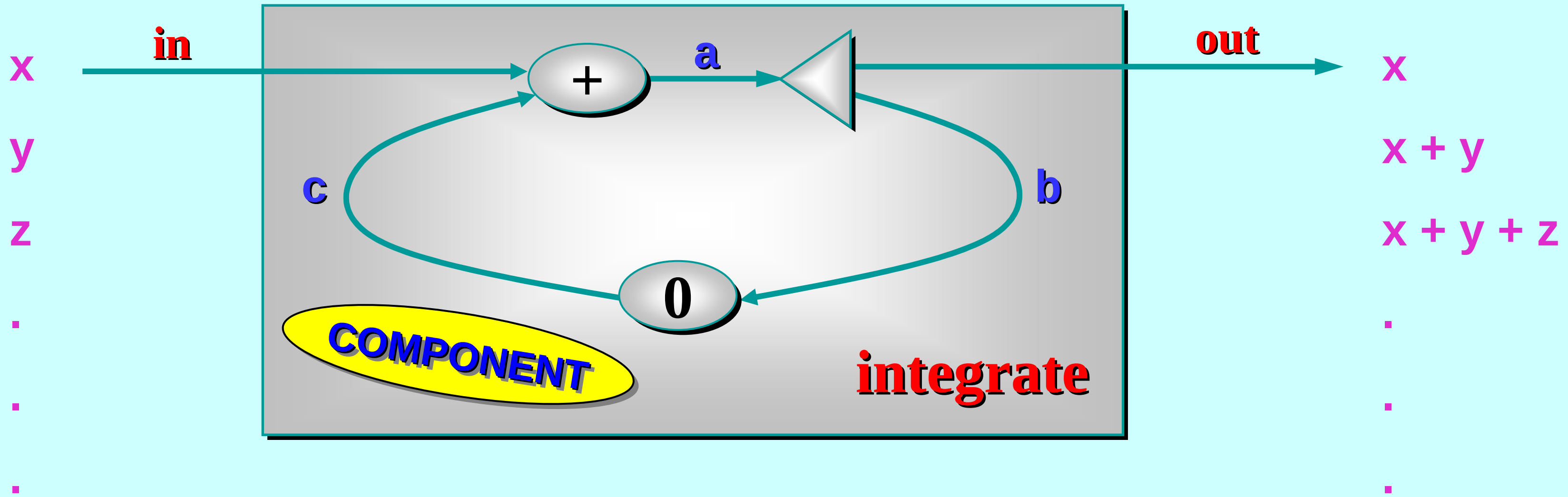
serial implementation

Choosing between Multiple Events


```
WHILE ok          -- main loop
  INT x:
  PRI ALT
    kill ? x
      ok := FALSE
    in ? x
      SEQ
        total := total + x
        out ! total
```

serial implementation

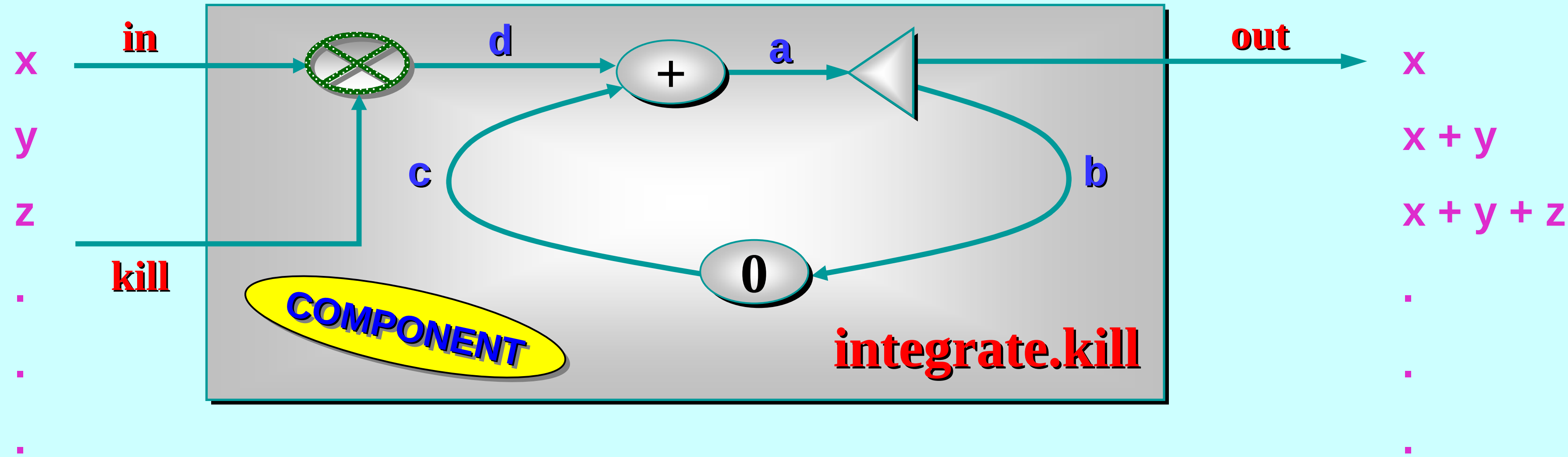
Parallel Process Networks




```
PROC integrate (CHAN INT in?, out!)
  CHAN INT a, b, c:
  PAR
    plus (in?, c?, a!)
    delta (a?, out!, b!)
    prefix (0, b?, c!)
:
```

parallel implementation

With an Added Kill Channel




```
PROC integrate.kill (CHAN INT in?, out !, kill?)
  CHAN INT a, b, c, d:
  PAR
    poison (in?, kill?, d!)
    plus (d?, c?, a!)
    delta (a?, out!, b!)
    prefix (0, b?, c!)
:
```

parallel implementation

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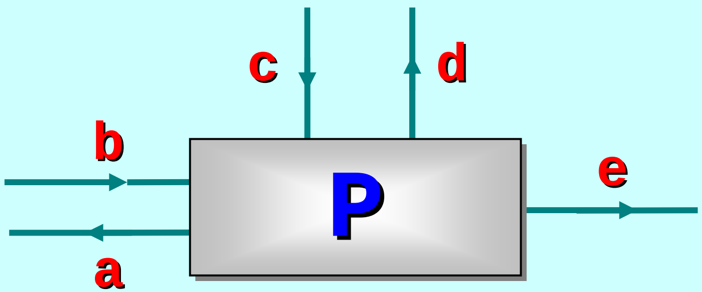
'Legoland' …

occam-π

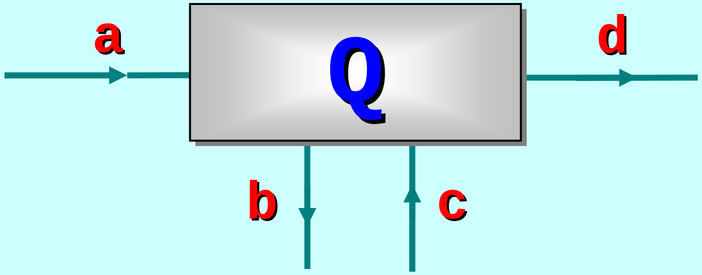
… from the top

(components, networks and communication)

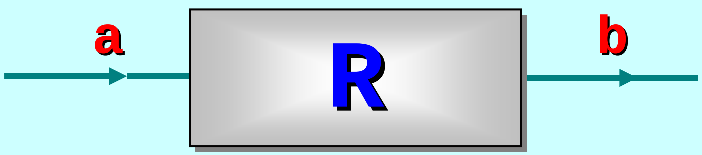
```
PROC P (CHAN INT a!, b?,
        CHAN BOOL c?,
        CHAN BYTE d!, e!)
  ...
:
```



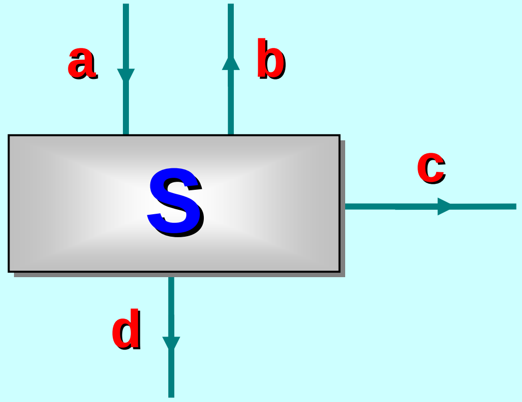

```
PROC Q (CHAN INT a?, b!, c?,
        CHAN BOOL d!)
  ...
:
```



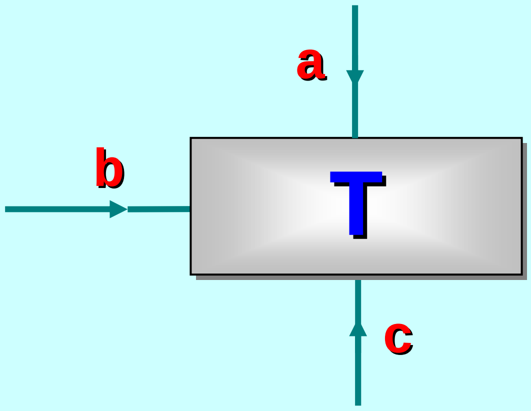

```
PROC R (CHAN BYTE a?, b!)
  ...
:
```

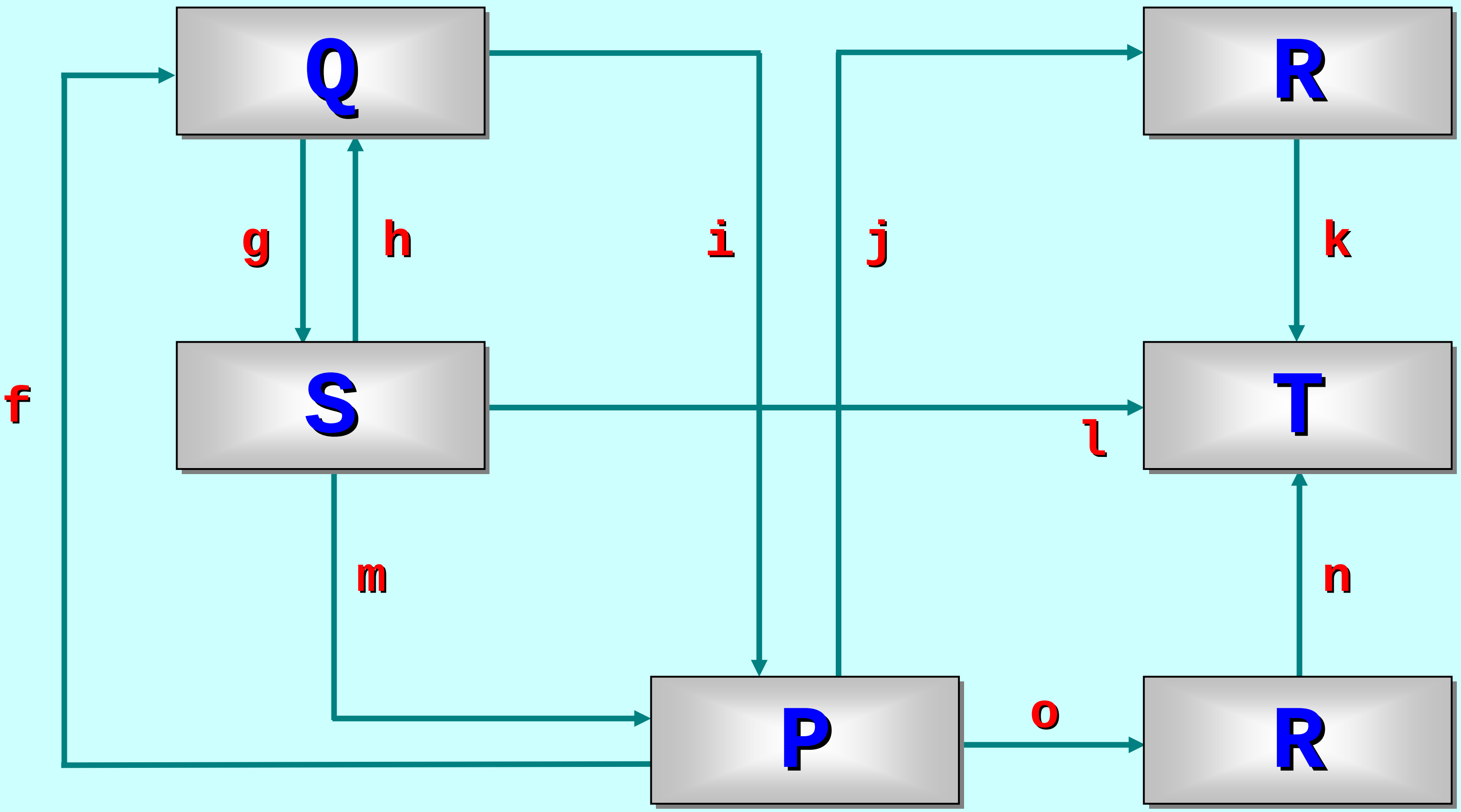


```
PROC S (CHAN INT a?, b!,
        CHAN BOOL c!,
        CHAN INT d!)
  ...
:
```




```
PROC T (CHAN BYTE a?,
        CHAN BOOL b?,
        CHAN BYTE c?)
  ...
:
```




Q
R
g
h
i
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k
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S
T
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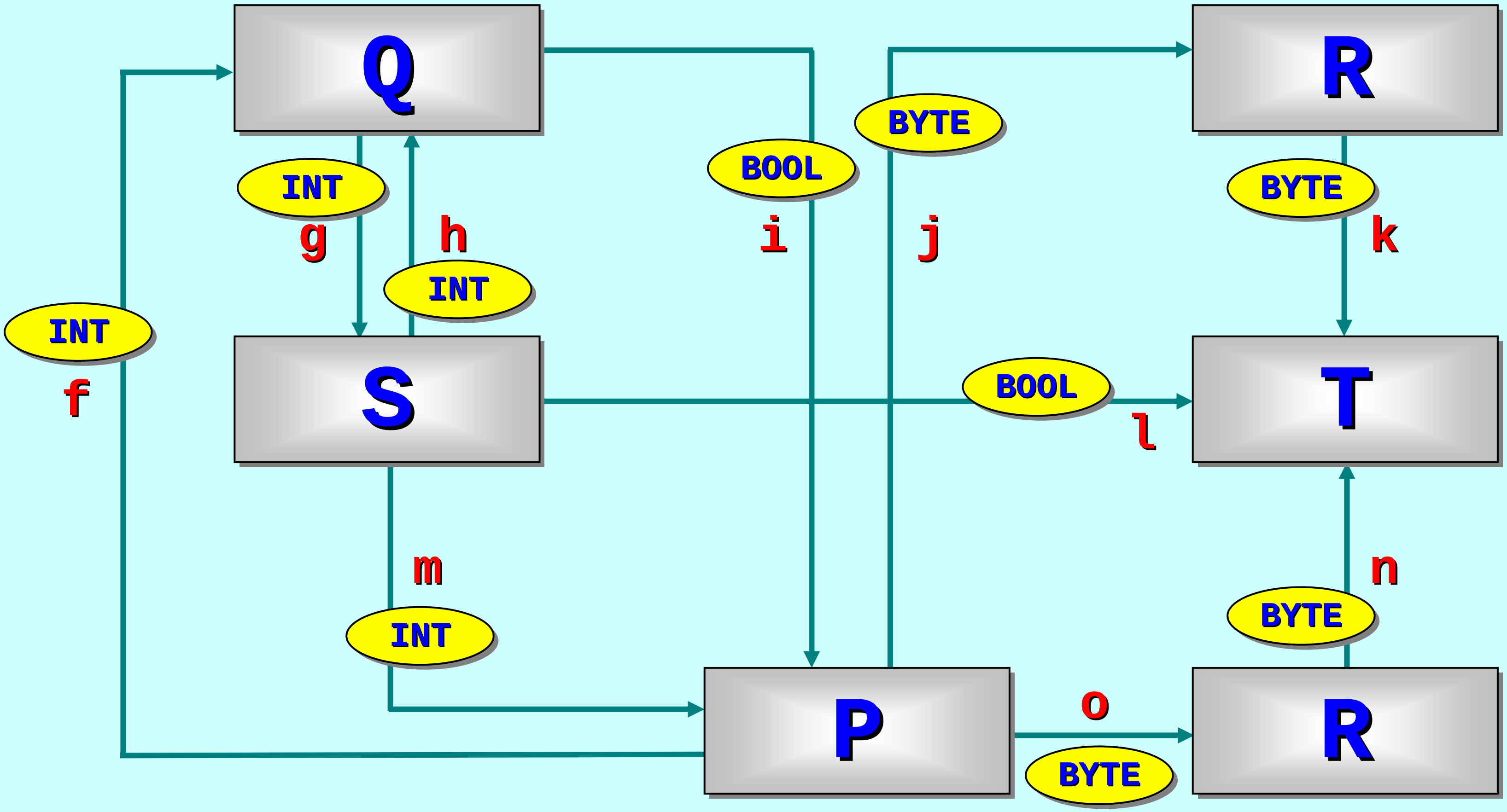
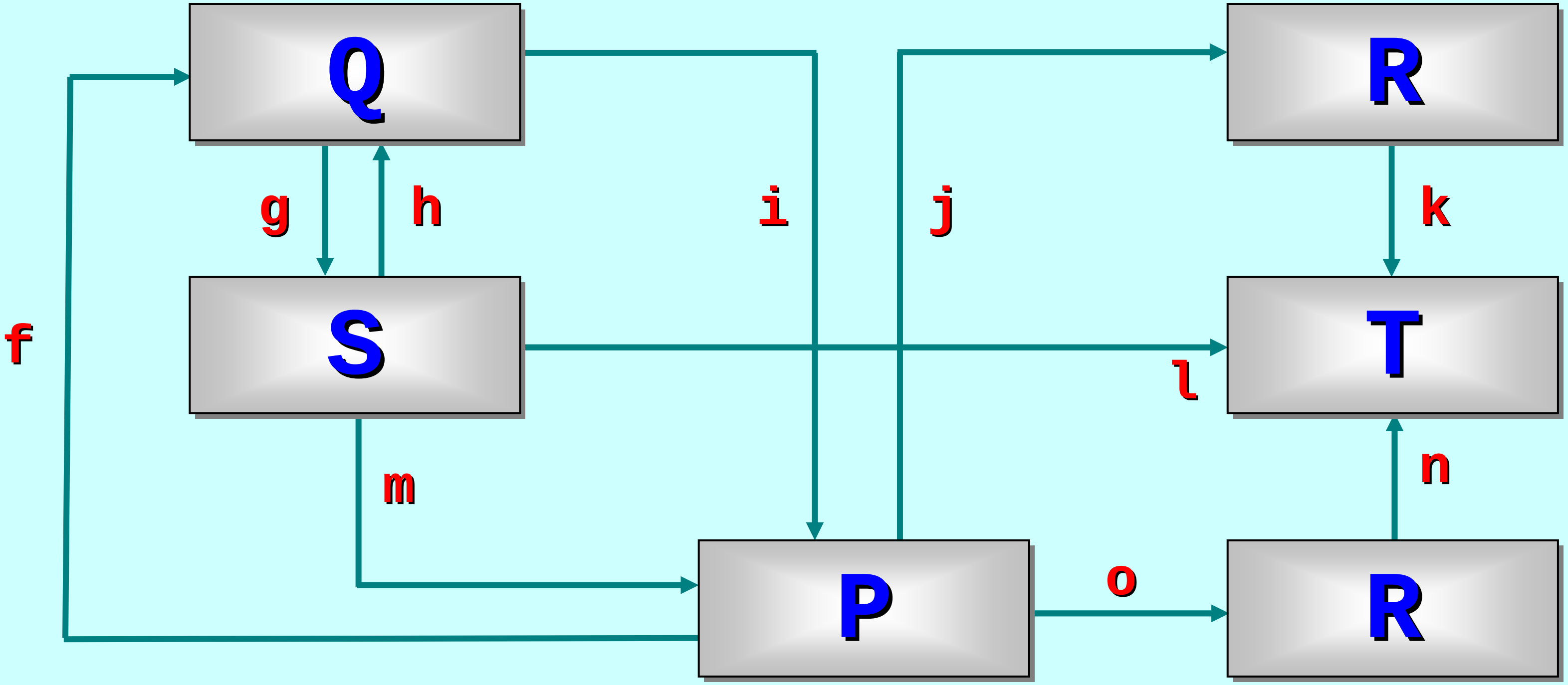
P
R

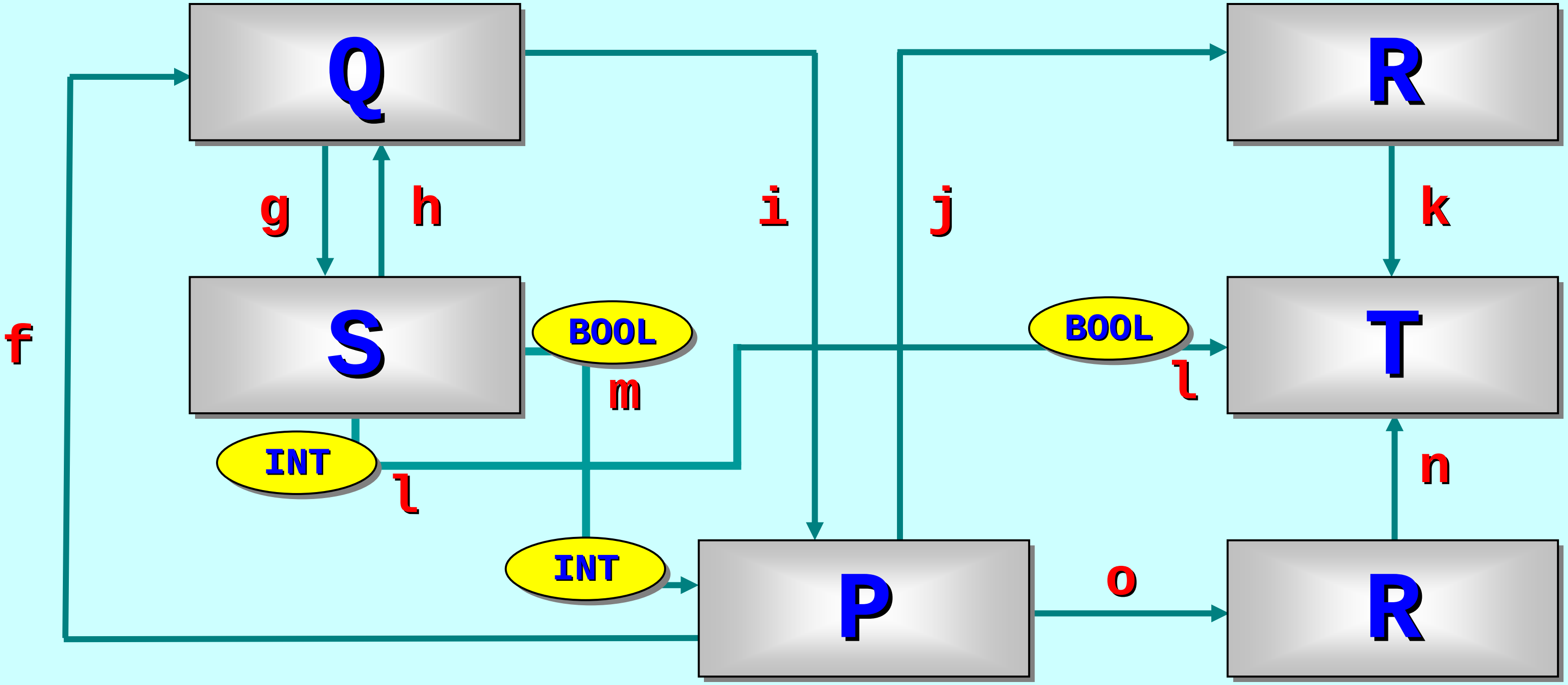



```
CHAN INT f, g, h, m:
CHAN BOOL i, l:
CHAN BYTE j, k, n, o:
```




```
CHAN INT f, g, h, m:
CHAN BOOL i, l:
CHAN BYTE j, k, n, o:
PAR
  P (f!, m?, i?, j!, o!)
  Q (f?, g!, h?, i!)
  R (j?, k!)
  R (o?, n!)
  S (g?, h!, m!, l!)
  T (k?, l?, n?)
```

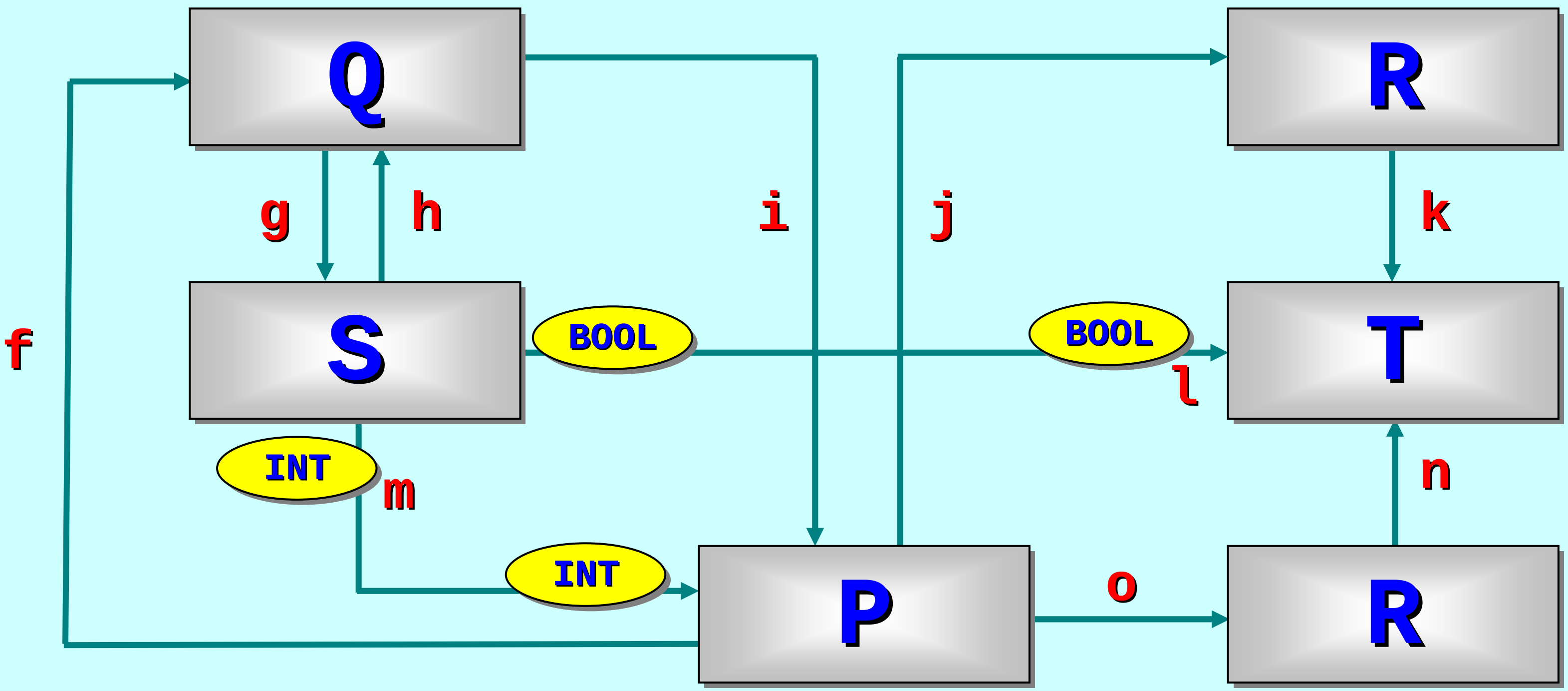
Spot the mistake ???




```
CHAN INT f, g, h, m:
CHAN BOOL i, l:
CHAN BYTE j, k, n, o:
PAR
  P (f!, m?, i?, j!, o!)
  Q (f?, g!, h?, i!)
  R (j?, k!)
  R (o?, n!)
  S (g?, h!, m!, l!)
  T (k?, l?, n?)
```

Picture & code agree

Bad wiring !!!

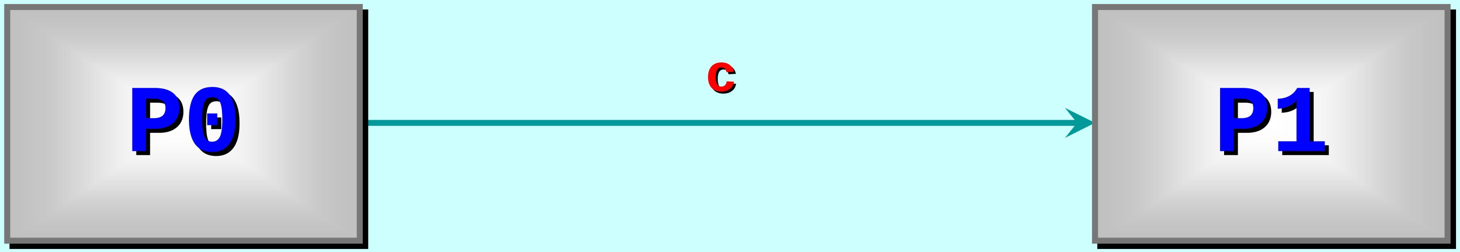



```
CHAN INT f, g, h, m:
CHAN BOOL i, l:
CHAN BYTE j, k, n, o:
PAR
  P (f!, m?, i?, j!, o!)
  Q (f?, g!, h?, i!)
  R (j?, k!)
  R (o?, n!)
  S (g?, h!, l!, m!)
  T (k?, l?, n?)
```

Picture & code agree

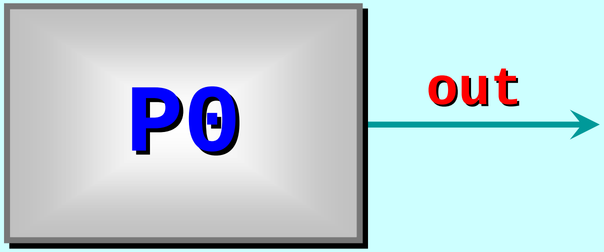
Good wiring !!!

Synchronised Unbuffered Communication

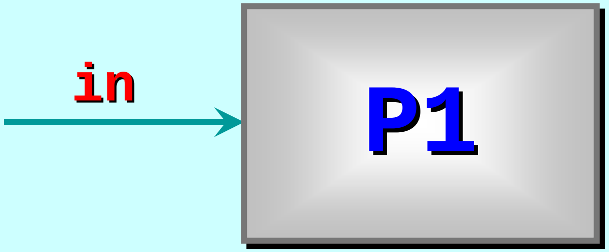



```
CHAN INT c:
PAR
  P0 (c!)
  P1 (c?)
```

```
PROC P0 (CHAN INT out!)
  .
  .
  .
  out ! value
  .
  .
  .
:
```




```
PROC P1 (CHAN INT in?)
  .
  .
  .
  in ? x
  .
  .
  .
:
```



Synchronised Unbuffered Communication

```
out ! value
```

- Output **`value`** down the channel **`out`**
- This operation does not complete until the process at the other end of the channel inputs the information
- Until that happens, the outputting process sleeps (possibly forever!)

Synchronised Unbuffered Communication

```
in ? x
```

- Input the next piece of information from channel **`in`** into the variable **`x`**
- This operation does not complete until the process at the other end of the channel outputs the information
- Until that happens, the inputting process sleeps (possibly forever!)
- The inputting process can set “timeouts” on these inputs or choose between alternative inputs. [We will do this later]

Synchronised Unbuffered Communication *(“Rendezvous”)*

- Unified concept of *synchronisation* and *unbuffered communication*.
- *Asynchronous* and *buffered* communication are easy to construct (later).
- Incoming communications are *selectable*.
- *Hardware model:* it is fast to implement.
- *Hardware model:* our intuition enables us to reason about it (see the ***Legoland*** slides).

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Communicating processes ...

A flavour of occam-π …

Networks and communication …

Types, channels, processes …

Primitive processes …

Structured processes …

‘Legoland’ …

occam-π

... from the bottom

Types

Primitive types

```
INT, BYTE, BOOL
INT16, INT32, INT64
REAL32, REAL64
```

The precision of the **INT** type depends on the word-length of the target processor (e.g. 32 bits for the Intel Pentium)

Arrays types (indexed from 0)

```
[100]INT
[32][32][8]BYTE
[]REAL64
```

When the compiler or run-time system can work it out, we don't have to specify array sizes.

Record types

(later ...)

Operators

`+, -, *, /, \` `PLUS, MINUS, TIMES`	`INTxx, INTxx → INTxx` `BYTE, BYTE → BYTE`
`+, -, *, /, \`	`REALxx, REALxx → REALxx`

`<, <=, >=, >`	`INTxx, INTxx → BOOL`
	 `BYTE, BYTE → BOOL`
	 `REALxx, REALxx → BOOL`

`=, <>`	`*, * → BOOL`

precisions must match

types must match

There is *strong typing* for all expressions ...

Operators

`+, -, *, /, \`
`PLUS, MINUS,`
`TIMES`
	INTxx, INTxx → INTxx
	BYTE, BYTE → BYTE

`+, -, *, /, \`	REALxx, REALxx → REALxx
`<, <=, >=, >`	INTxx, INTxx → BOOL BYTE, BYTE → BOOL REALxx, REALxx → BOOL
`=, <>`	*, * → BOOL

NB: this is *modulo*

There is ***strong typing*** for all expressions ...

Expressions

No *auto-coercion* happens between types: if **`x`** is a **`REAL32`** and **`i`** is an **`INT`**, then **`x + i`** is illegal ...

Where necessary, explicit *casting* between types must be programmed: e.g. **`x + (REAL32 ROUND i)`** ...

To cast between types, use the *target type name* as a prefix operator.

If *rounding mode* is significant, this must be specified (**`ROUND`** or **`TRUNC`**) following the *target type name* (as above).

No *precedence* is defined between operators, we must use brackets: e.g. **`a + (b*c)`** ...

Expressions

The operators `+`, `-`, `*` and `/` trigger run-time errors if their results overflow.

In Java and C, such errors are ignored.

Therefore, the operators `+` and `*` are *non-associative* and we must use more brackets: e.g. `a + (b + c)` ...

The `INT` operators `PLUS`, `MINUS` and `TIMES` *wrap-around* (i.e. do not trigger run-time errors) if the results overflow.

The **occam-π** `PLUS`, `MINUS` and `TIMES` are the same as the Java/C `+`, `-` and `*`.

`PLUS`, `MINUS` and `TIMES` are mainly used for calculating *timeouts*.

Operators

`AND, OR`	`BOOL, BOOL` → `BOOL`	*Boolean* **logic**
`NOT`	`BOOL` → `BOOL`	
`AFTER`	`INTxx, INTxx` → `BOOL`	*time* **compare**

`AFTER` relates to `>` in the same way as `PLUS` relates to `+`.

They both do arithmetic operations, but the former ignores overflow. If (`0` < `t` <= `MOSTPOS INTxx`), then (`s PLUS t`) is `AFTER s`, even if *wrap-around* occurs and (`s PLUS t`) is `< s`.

There is *strong typing* for all expressions ...

Operators

not *and* *or* *exclusive-or*

`/\, \/, ><`

INTxx, INTxx → INTxx
BYTE, BYTE → BYTE

`~`

INTxx → INTxx
BYTE → BYTE

***bitwise* logic**

`<<, >>`

INTxx, INTxx → INTxx
BYTE, BYTE → BYTE

***bitwise* shifts**

left shift *right shift*

There is ***strong typing*** for all expressions ...

Values (named constants)

```
VAL INT max IS 50:
VAL INT double.max IS 2*max:

VAL BYTE letter IS 'A':

VAL []BYTE hello IS "Hello*c*n":

VAL []INT mask IS [#01, #02, #04, #08,
                   #10, #20, #40, #80]:
```

special chars

hexadecimal

All *declarations* end in a colon ...

A declaration cannot be used *before* it is made ...

Character literals have type **BYTE** (their *ASCII* value) ...

String literals have type **[]BYTE** ...

Values (named constants)

```
VAL INT max IS 50:
VAL INT double.max IS 2*max:

VAL BYTE letter IS 'A':

VAL []BYTE hello IS "Hello*c*n":

VAL []INT mask IS [#01, #02, #04, #08,
                   #10, #20, #40, #80]:
```

special chars

hexadecimal

The compiler fills in the sizes of the **hello** and **mask** arrays for us. We could have done this ourselves (**[7]BYTE** and **[8]INT** respectively).

Declarations are aligned at the same level of indentation ...

Long lines may be broken after commas, etc. ...

Variable Declarations

```
INT a, b:
[max]INT c:
[double.max]BYTE d:
```

two integers

50 integers

100 integers

Timer Declarations

```
TIMER tim:
```

one timer

Channel Declarations

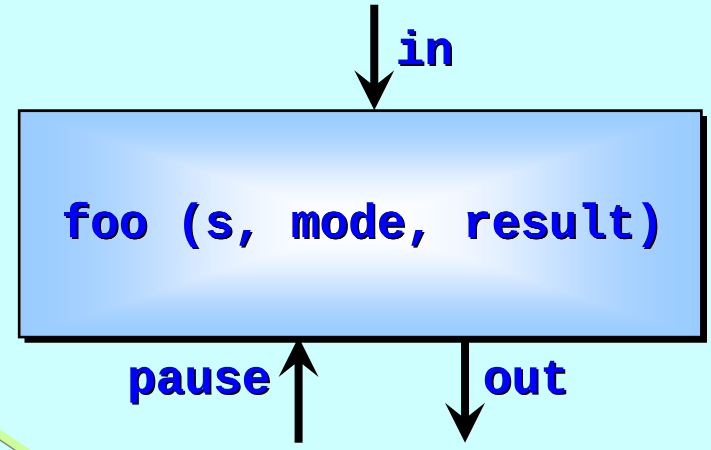
```
CHAN BYTE p:
[max<<2]CHAN INT q:
```

a single channel

200 channels

Process Abstractions

```
PROC foo (VAL []BYTE s,
          VAL BOOL mode,
          INT result,
          CHAN INT in?, out!,
          CHAN BYTE pause?)
  ...
:
```



process body

CHANnel parameters – for communicating with other processes ...

```
VAL <type> <id>
```

VALue (data) parameters – local constants within the **PROC** body ...

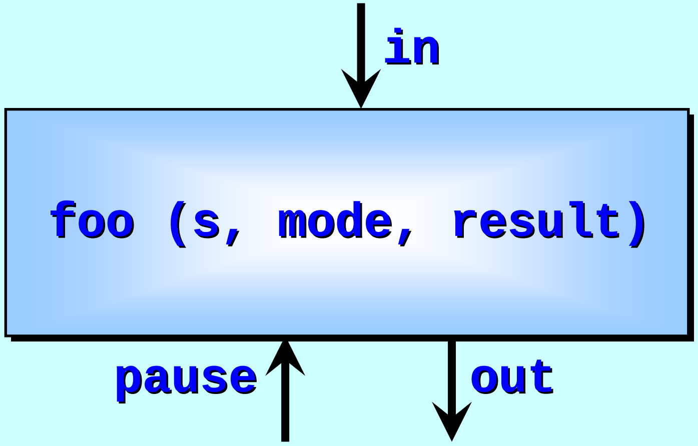
```
<type> <id>
```

reference (data) parameters – may be changed within the **PROC** body (with effect on the invoking process) ...

Process Abstractions

```
PROC foo (VAL []BYTE s,
          VAL BOOL mode,
          INT result,
          CHAN INT in?, out!,
          CHAN BYTE pause?)
  ...
:
```

process body



We have just used the *three dot notation* as a place holder for the **PROC** body. Code (including any local declarations) goes here. The *three dots* are not part of **occam-π** syntax!

Note that the **PROC** body is indented (two spaces) from its **PROC** header and closing colon.

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An occam-π Process (*syntax*)

Syntactically, an **occam-π** process consists of:

... an *optional* sequence of declarations (e.g. values, variables, timers, channels, procs, channel protocols*, ports*, data types*, channel types*, process types*, barriers*, ...)

... a single executable process

All the declarations – and the executable – are aligned at the same level of indentation.

** later ...*

Primitive Processes

Assignment

```
a := c[2] + b
```

data types on either side of the assignment must match

Input *(synchronising)*

```
in ? a
```

the data type being communicated must match the channel type

Output *(synchronising)*

```
out ! a + (2*b)
```

There are *strong typing* rules ...

Primitive Processes

What's the time?

```
tim ? t
```

where ...

```
TIMER tim:
INT t:
```

Timeout *(wait until specified time)*

```
tim ? AFTER (t PLUS 3000)
```

Null *(do nothing)*

```
SKIP
```

Suspend *(non-recoverable)*

```
STOP
```

+ **BARRIER** *synchronisation, ...*
(later)

A Brief History of Time

What's the time?

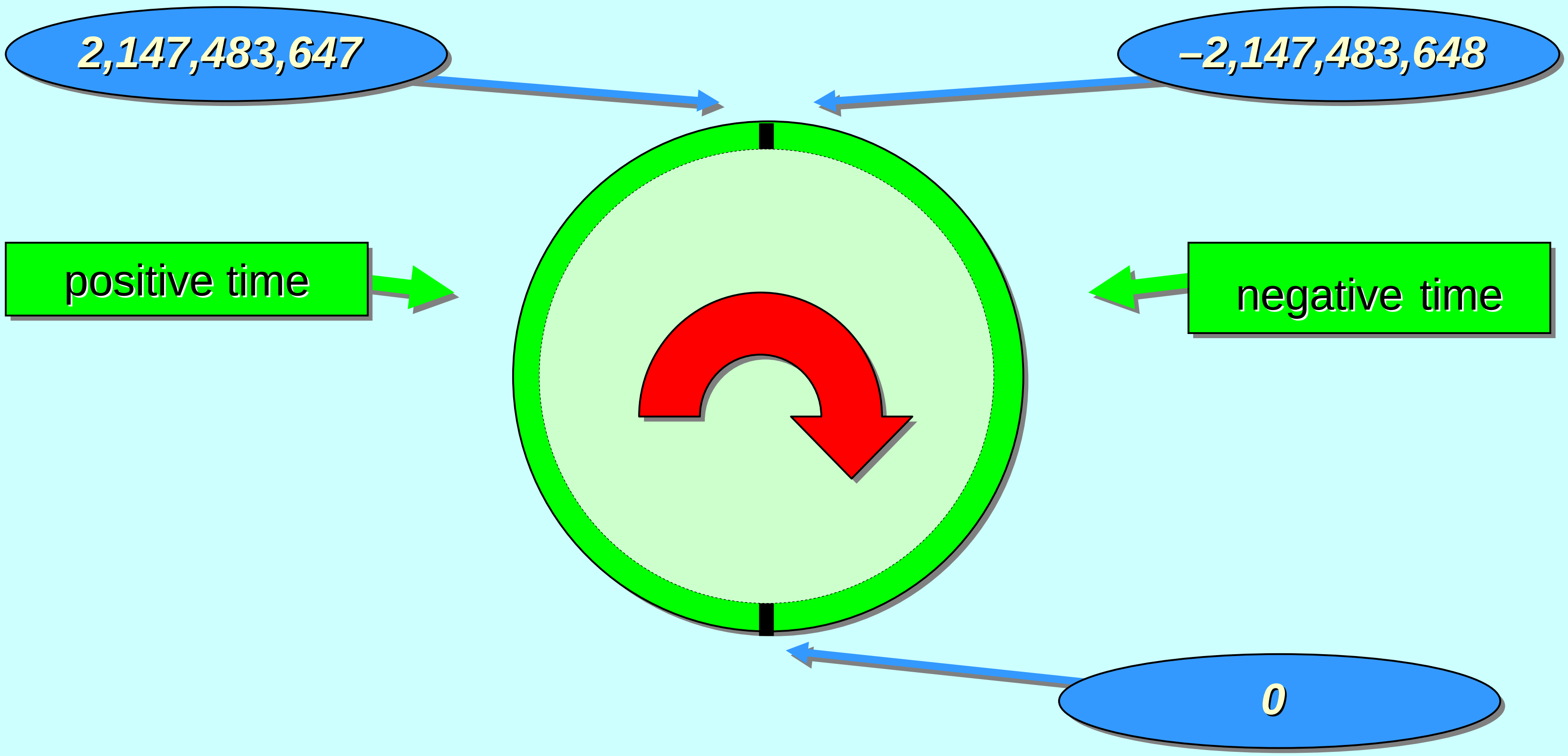
```
tim ? t
```

```
TIMER tim:
INT t:
```

occam-π time values are **INT**s delivered by **TIMER**s. These values increment by one every microsecond (for all current, 10/2006, implementations).

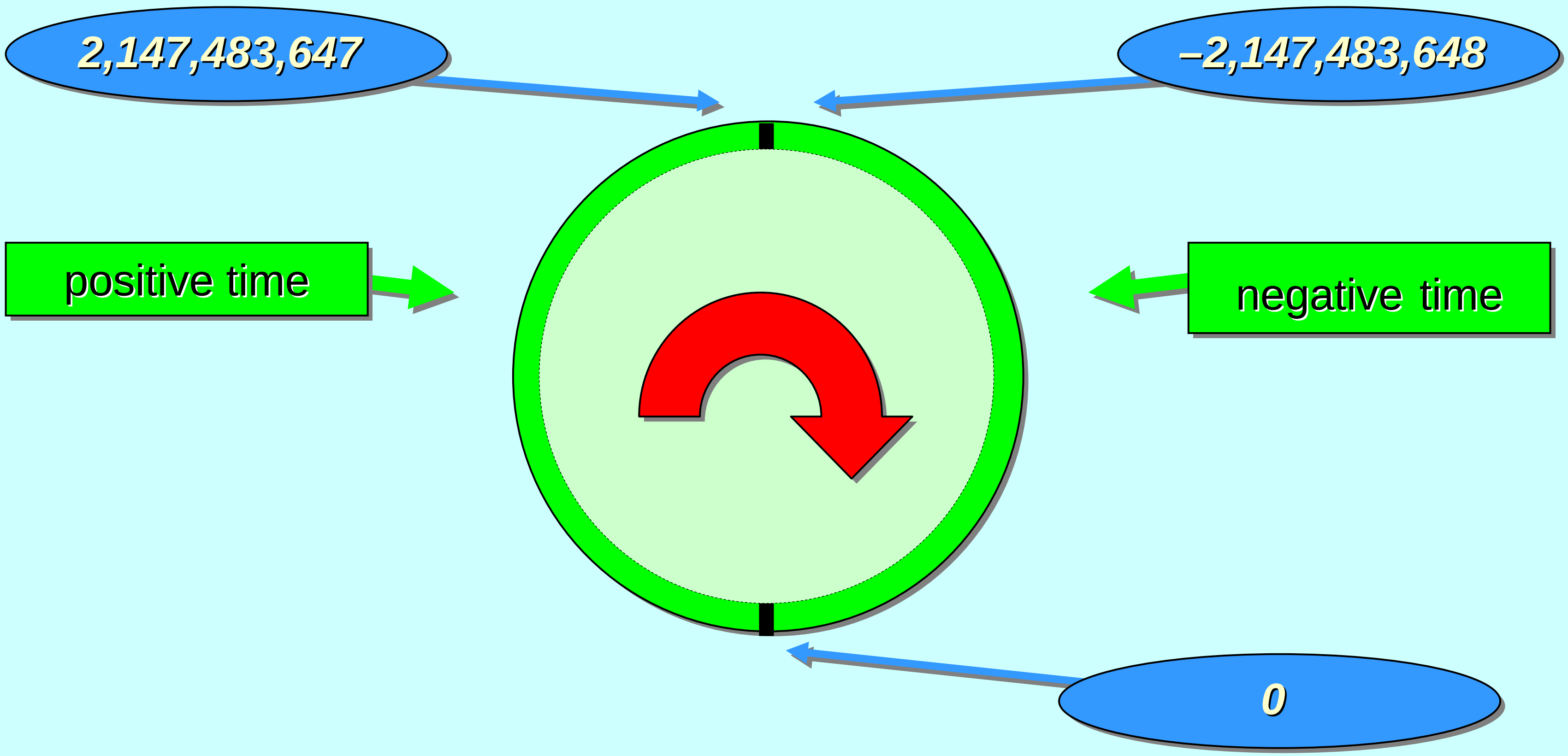
occam-π time values *cycle* through all **INT** values – from the most negative (**MOSTNEG INT**), through zero (**0**), to the most positive (**MOSTPOS INT**) and, then, back to the most negative again. occam-π time *starts* at an *arbitrary* **INT** value.

A Brief History of Time



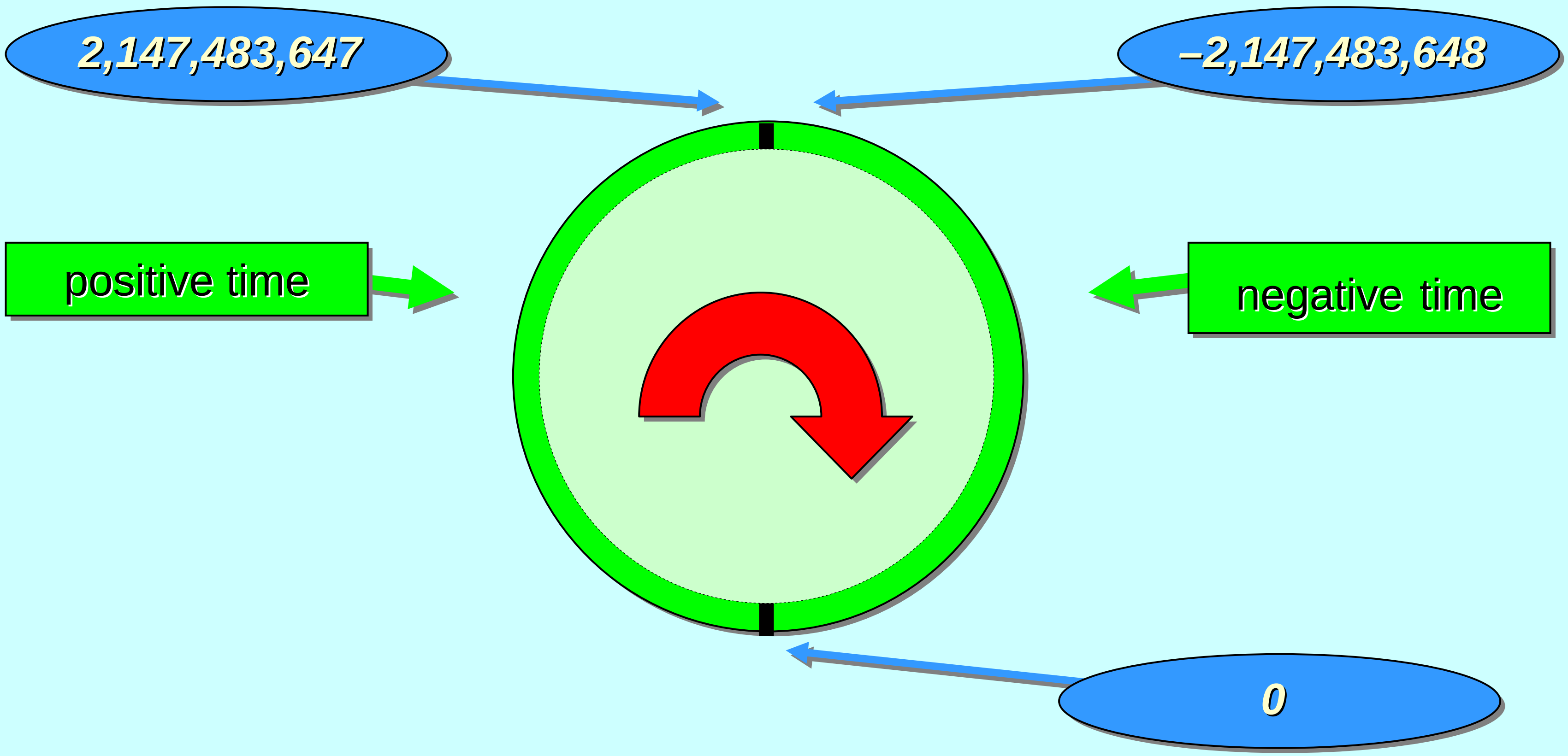
For 32-bit **INT**s incrementing every microsecond, **occam-π** time values *cycle* every **72** minutes (roughly).

A Brief History of Time



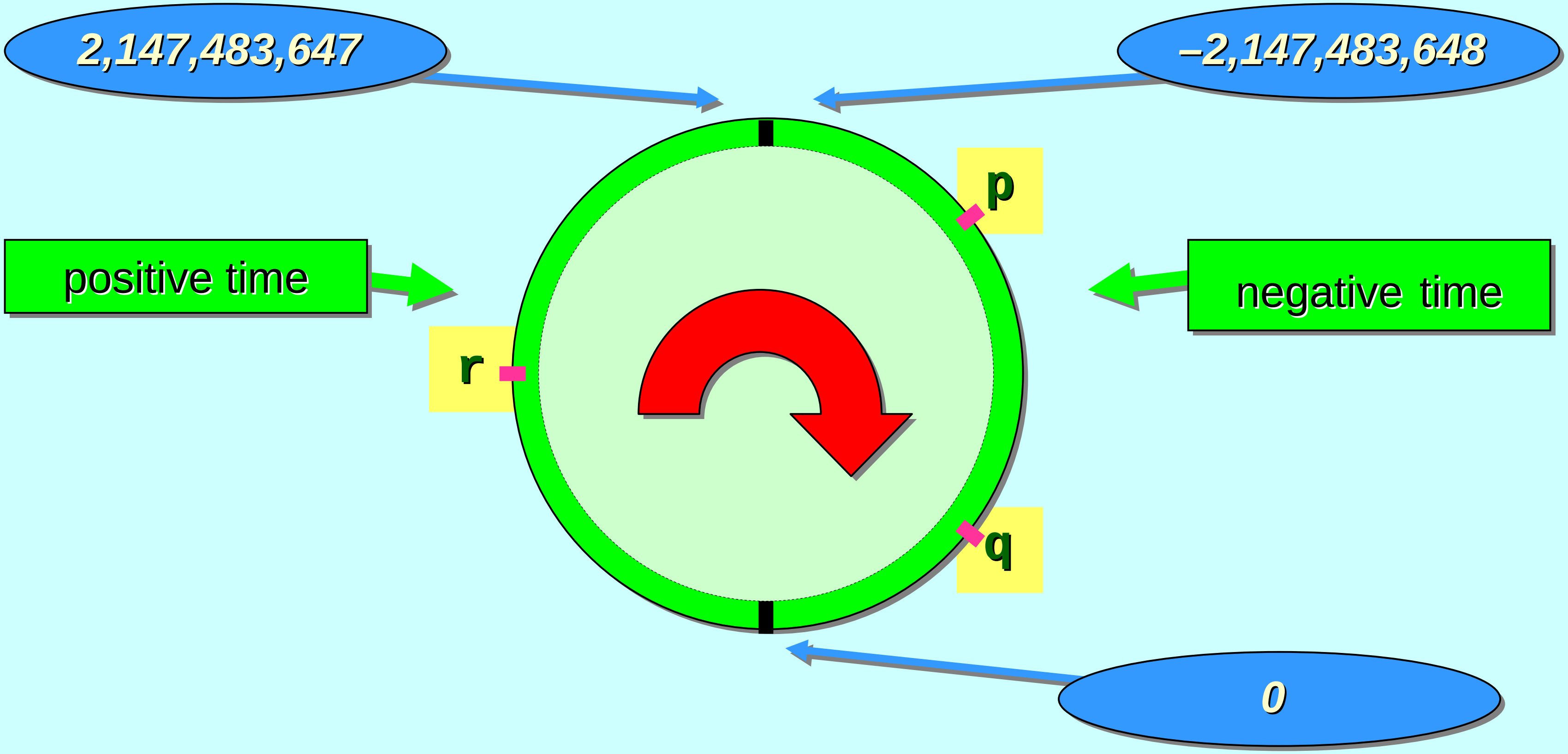
Note that **occam-π** time values increment according to the rules for **`PLUS`** *(wrap-around)*.

A Brief History of Time



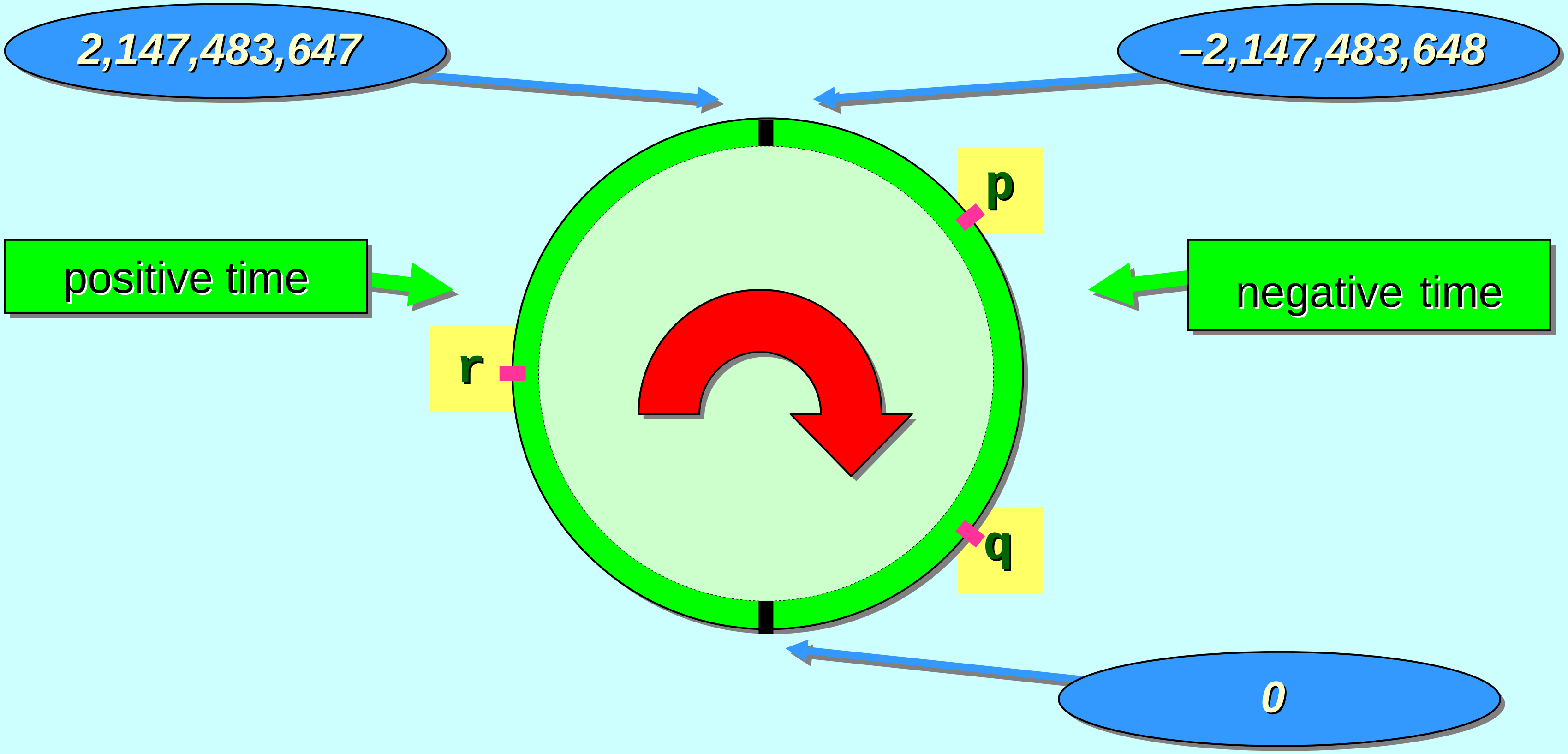
So, (**a AFTER b**) is **TRUE** if and only if the distance from **b** to **a** going *clockwise* – in the above diagram – is *less than* the distance going *anti-clockwise*.

A Brief History of Time



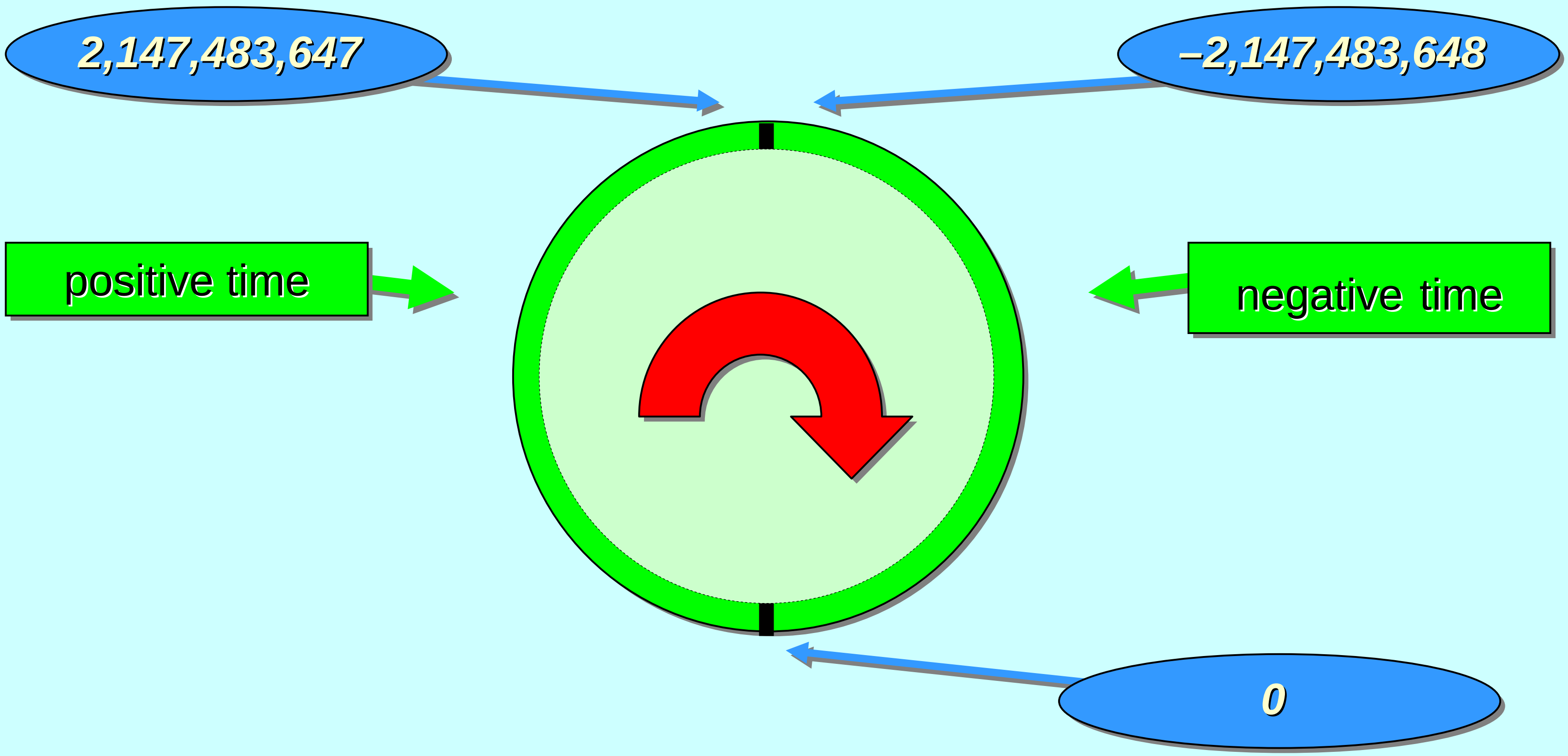
Above, we have (**`q AFTER p`**), (**`r AFTER q`**) and (**`p AFTER r`**). Think of **`p`**, **`q`** and **`r`** as **2**, **4** and **9** on a 12-hour clock face and ignore whether they represent *am* or *pm*.

A Brief History of Time



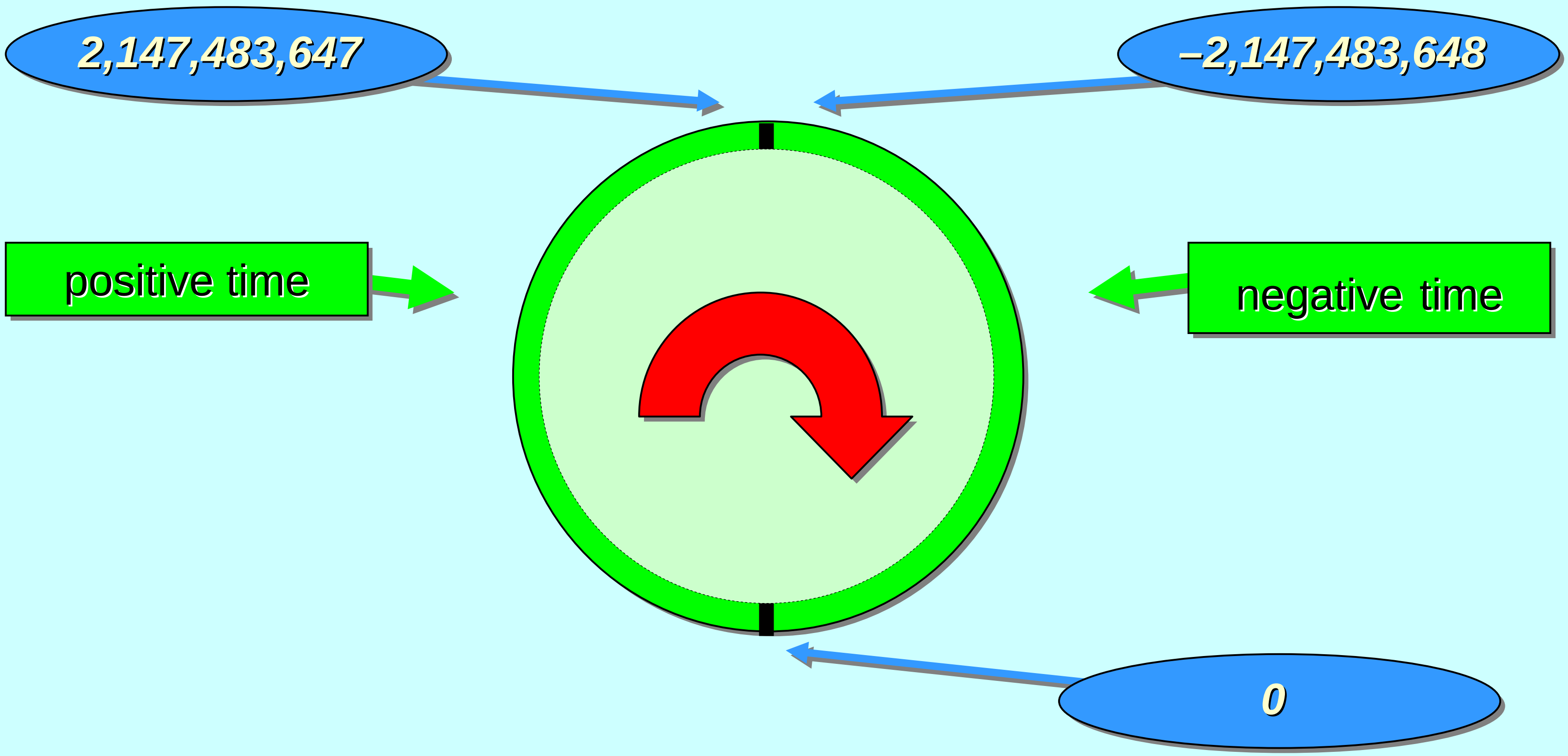
Above, we have (**`q AFTER p`**), (**`r AFTER q`**) and (**`p AFTER r`**).
Note that, using normal arithmetic, we have (**`q > p`**) and (**`r > q`**) ,
but not (**`p > r`**).

A Brief History of Time



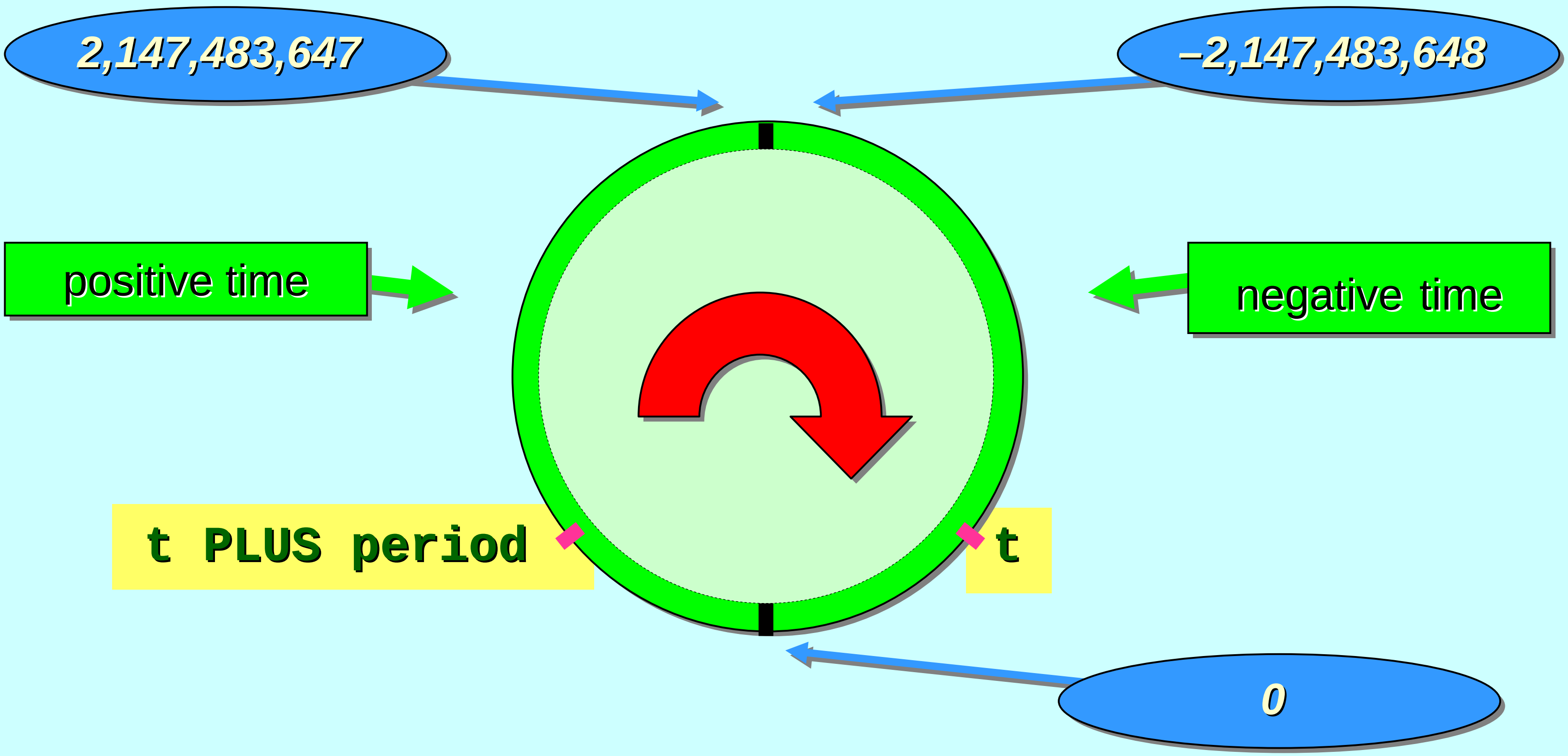
Therefore, so long as our *timeout periods* are less than **36** minutes (i.e. half the *time cycle*) and we calculate *absolute timeout values* using **PLUS**, the **AFTER** operator always gives the expected time comparisons – even if the time *wrap-around* occurs.

A Brief History of Time



Real-time systems tend to deal in *microseconds* or *milliseconds*, so **36** minutes is a luxury! If we need to address longer timeouts, some extra (simple) programming effort is required.

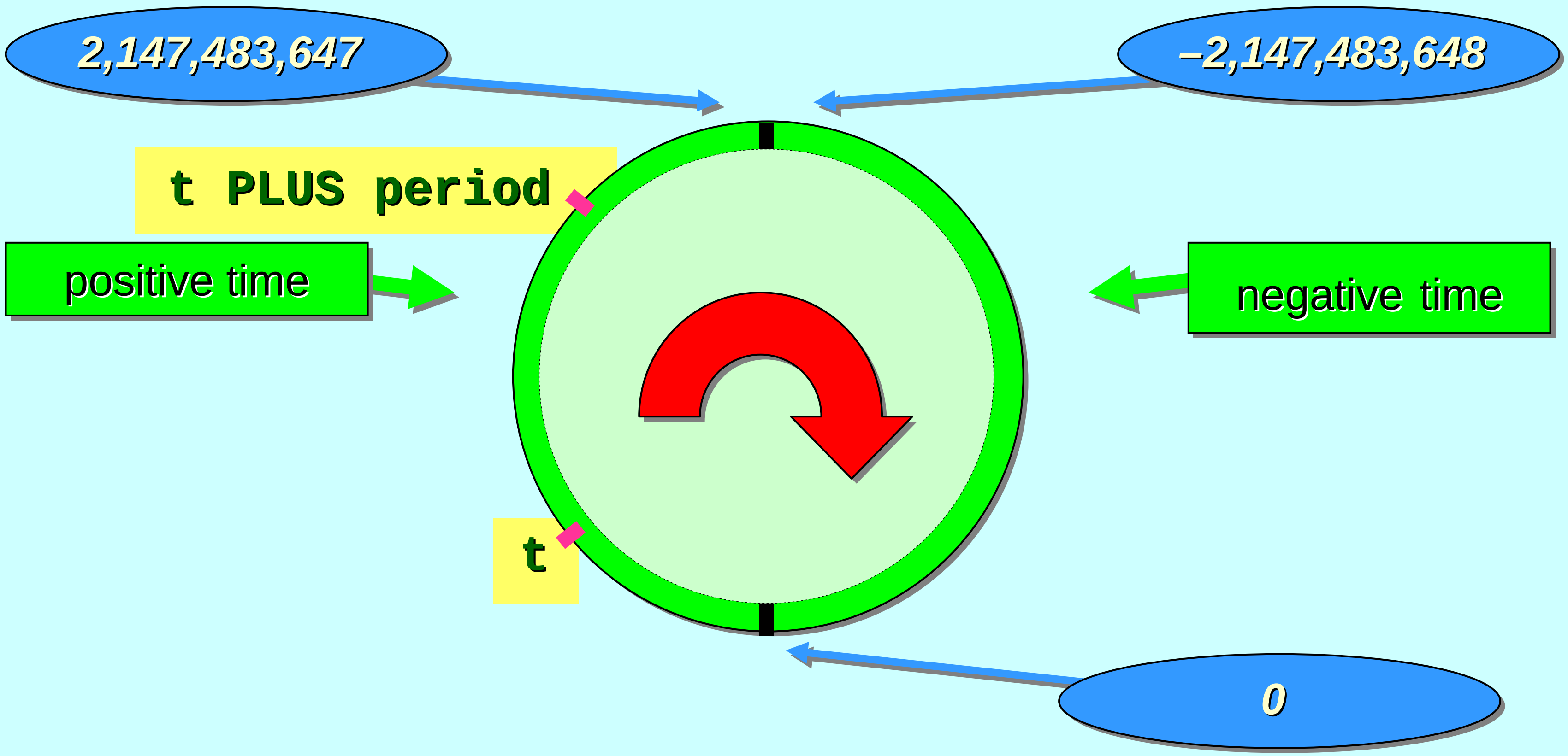
A Brief History of Time




```
SEQ
  tim ? t
  tim ? AFTER (t PLUS period)
```

OK, provided period < 36 minutes

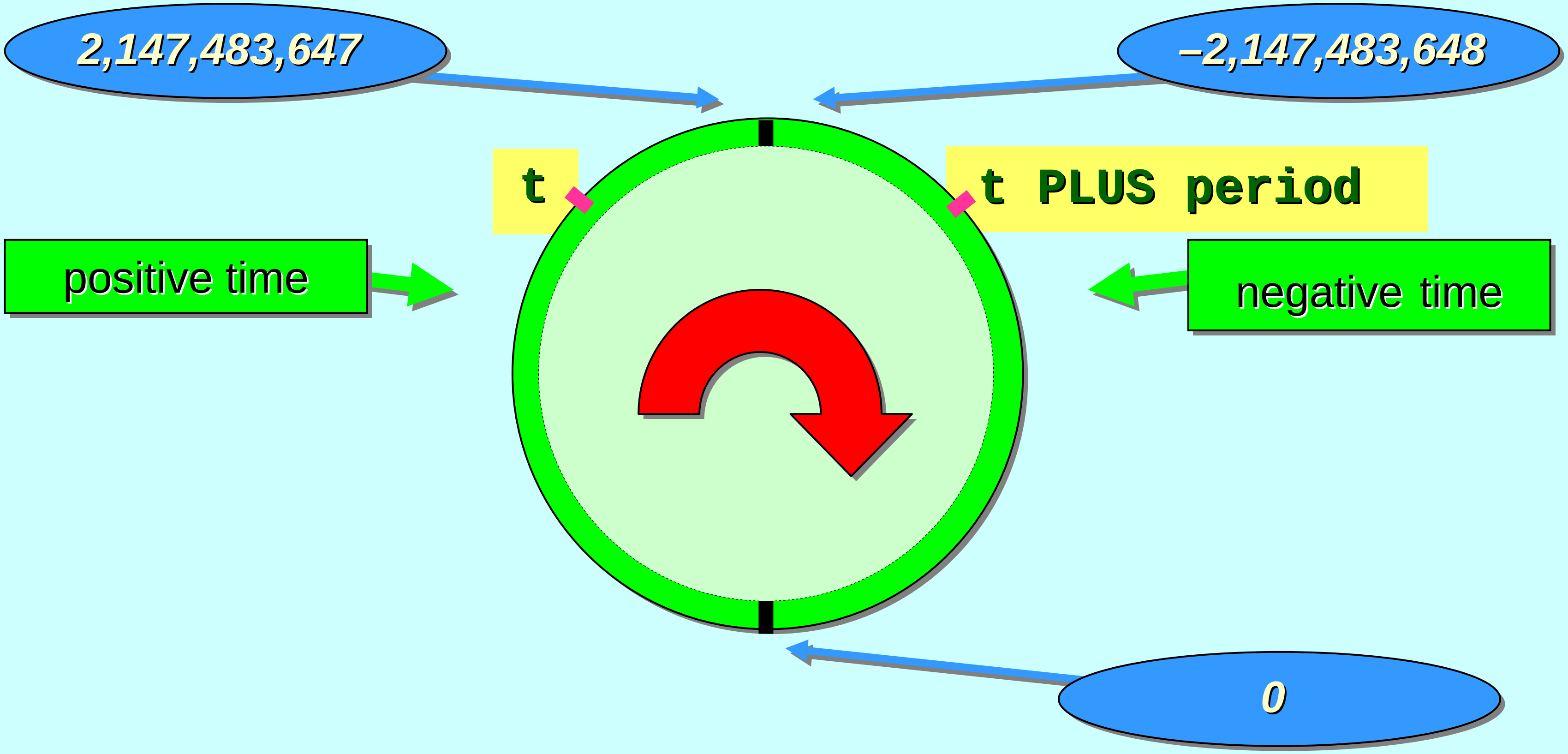
A Brief History of Time




```
SEQ
  tim ? t
  tim ? AFTER (t PLUS period)
```

OK, provided **period** < 36 minutes

A Brief History of Time




```
SEQ
  tim ? t
  tim ? AFTER (t PLUS period)
```

OK, provided `period` < 36 minutes

Some occam-π Basics

Communicating processes ...

A flavour of occam-π …

Networks and communication …

Types, channels, processes …

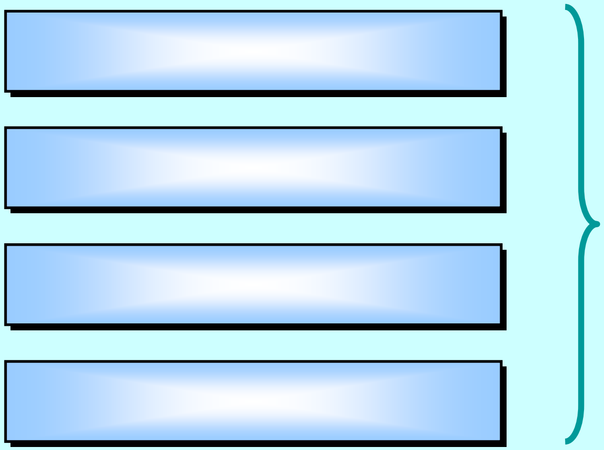
Primitive processes …

Structured processes …

'Legoland' …

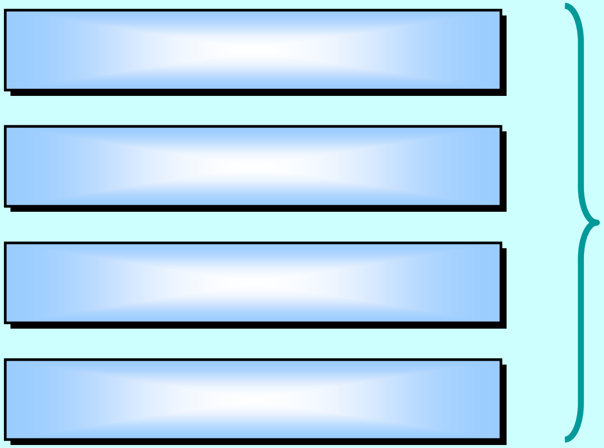
Structured Processes (SEQ and PAR)

SEQ



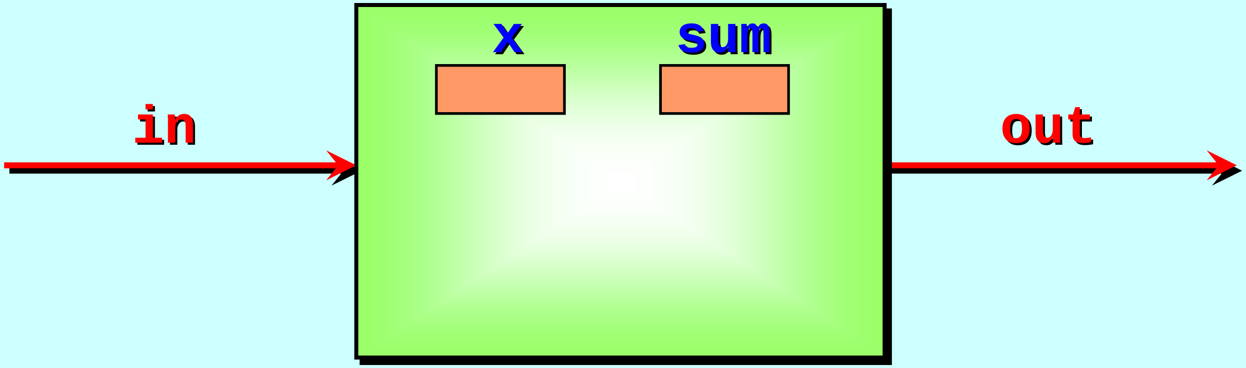
Do these 4 processes in the sequence written

PAR



Do these 4 processes in parallel

Structured Processes (SEQ example)

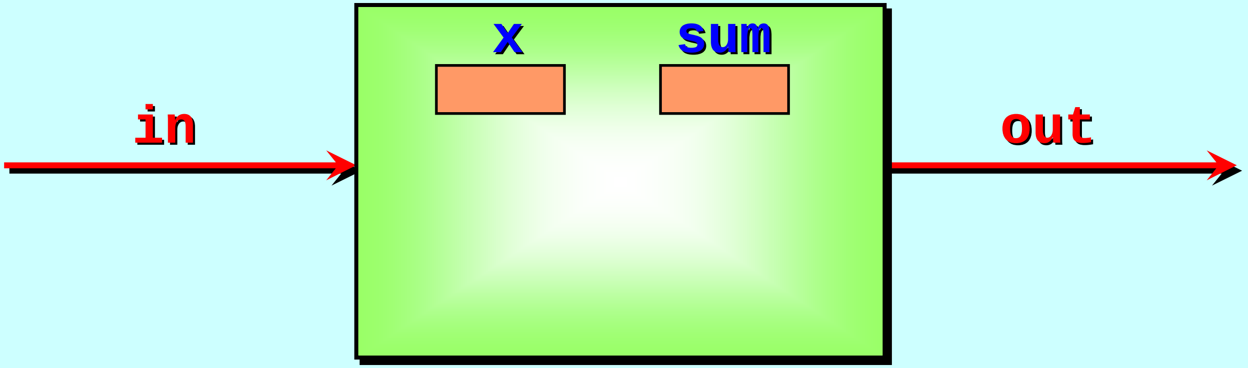


Here is a machine with internal *variables* **x** and **sum** – assume they are identical numeric types (e.g. **INT**).

Let's assume the external channels carry the same type.

Consider the following fragment of code ...

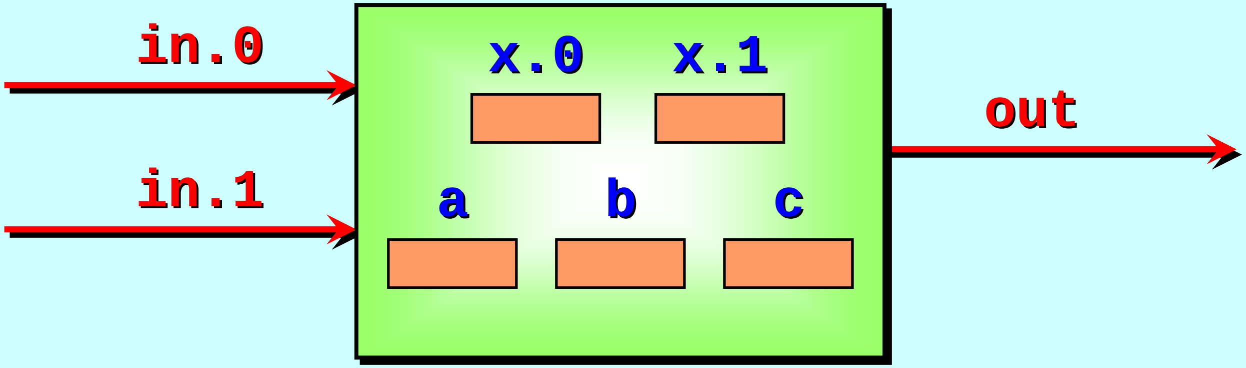
Structured Processes (SEQ example)




```
SEQ
  in ? sum
  in ? x
  sum := sum + x
  out ! sum
```

Any change in the order
of these processes
impacts the semantics ...

Structured Processes (PAR example)

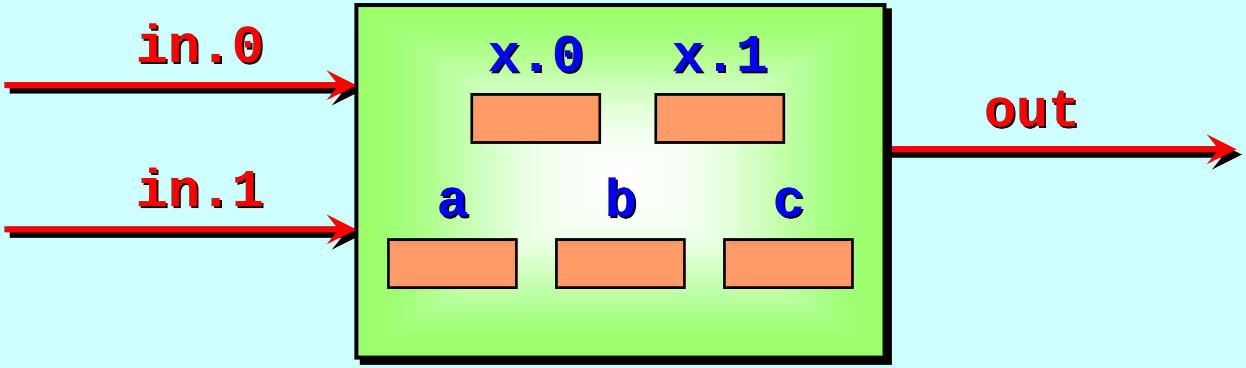


Here is another machine with internal *variables* **`x.0`**, **`x.1`**, **`a`**, **`b`** and **`c`** – assume they are identical numeric types (e.g. **`INT`**).

Let's assume the external channels carry the same type.

Consider the following fragment of code ...

Structured Processes (PAR example)




```
PAR
  in.0 ? x.0
  in.1 ? x.1
  out ! a + b
  c := a + (2*b)
```

The order in which these processes run does not matter ...

Structured Processes (PAR rules)

PAR

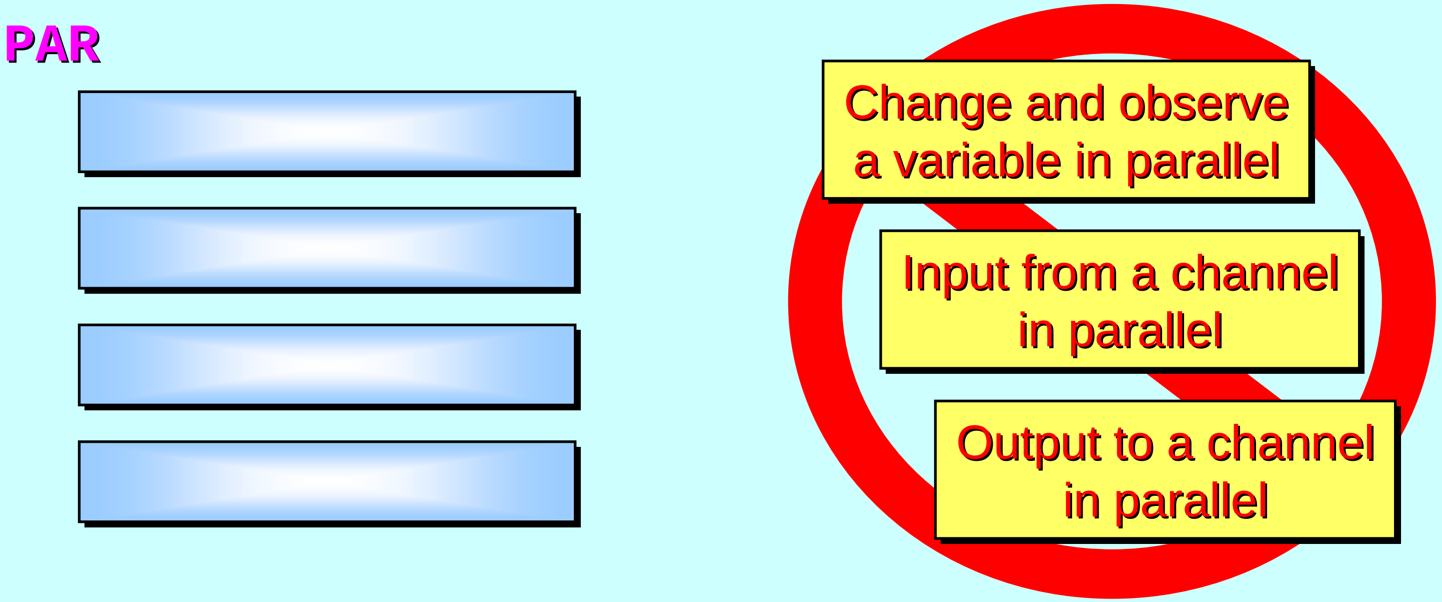
Change and observe a variable in parallel

Input from a channel in parallel

Output to a channel in parallel

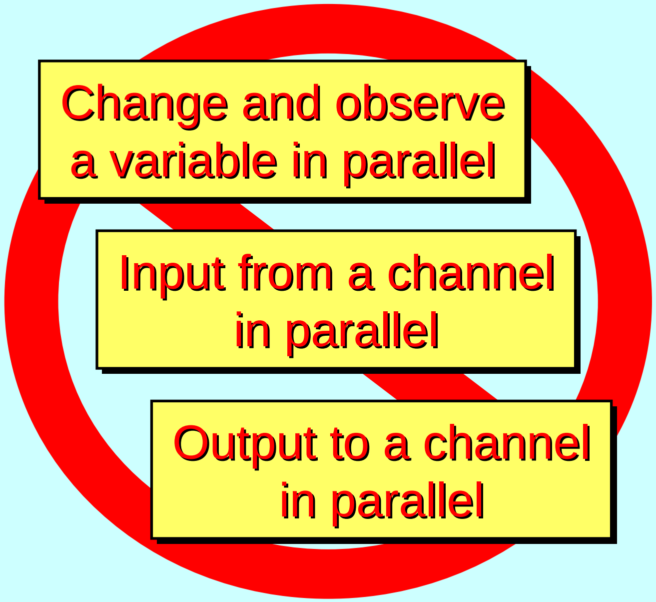
Parallel processes may not ...

Structured Processes (PAR rules)



The effect of these rules is that the processes cannot interfere with each other's state. If they need to interact, they must explicitly communicate.

Structured Processes (PAR rules)



No *data race hazards* are possible. The processes are safe to be scheduled ***in any order*** (e.g. on a single-core processor) or ***in parallel*** (e.g. on a multi-core processor).

Structured Processes (IF)

IF

<boolean>

<boolean>

<boolean>

<boolean>

The **_<boolean>_** conditions are evaluated in sequence. Only the process underneath the *first* **TRUE** one is executed.

If *all* the tests are **FALSE**, a run-time error is raised.

Structured Processes (IF example)

```
IF
  x > 0
    screen ! 'p‘
  x < 0
    screen ! 'n'
  TRUE
    screen ! 'z'
```

The **<boolean>** conditions are evaluated in sequence. Only the process underneath the *first* **TRUE** one is executed.

If *all* the tests are **FALSE**, a run-time error is raised.

Structured Processes (**WHILE**)

WHILE ***<boolean>***

Conventional
"while-loop"

If the ***<boolean>*** is **TRUE**, the indented process is executed ... then ...

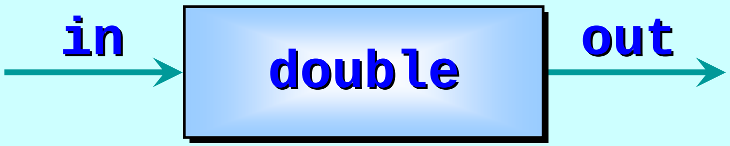
... the ***<boolean>*** is checked again ... if it is still **TRUE**, the indented process is executed again ... then ...

... etc. until ...

... the ***<boolean>*** is checked again ... and turns out to be **FALSE** ... in which case, this **WHILE** process terminates.

Structured Processes (WHILE example)

Here is a complete process (a *'chip'*) that doubles the values of the numbers flowing through it:

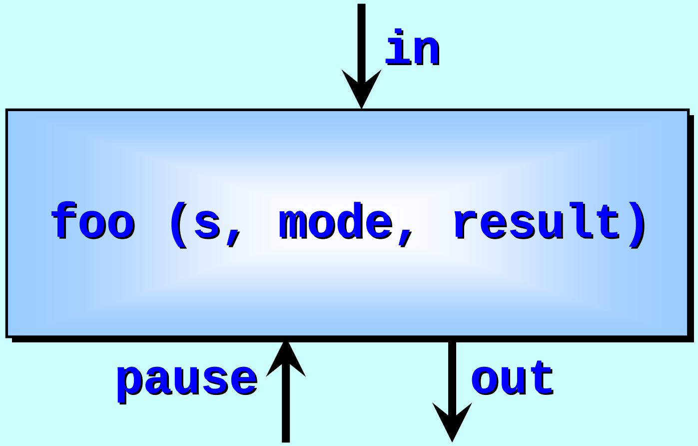



```
PROC double (CHAN INT in?, out!)
  WHILE TRUE
    INT x:
    SEQ
      in ? x
      out ! 2*x
:
```

runs forever …
☺☺☺

Structured Processes (PROC instance)

```
PROC foo (VAL []BYTE s,
          VAL BOOL mode,
          INT result,
          CHAN INT in?, out!,
          CHAN BYTE pause?)
  ...
:
```



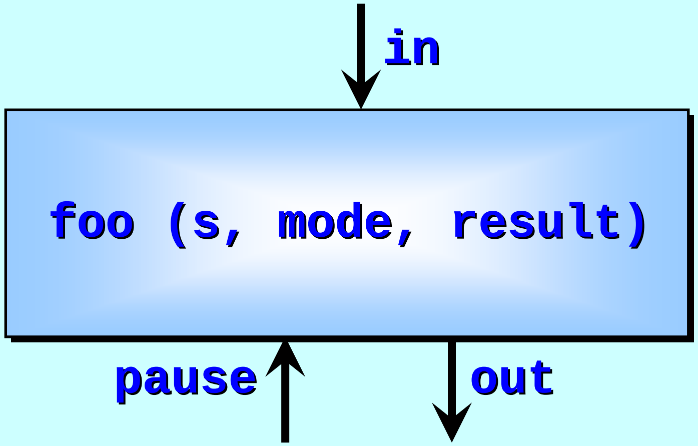
To create an instance, we must plug in correctly typed arguments – for example:

```
foo ("Goodbye World*c*n", TRUE, solution,
     q[i]?, q[i+1]!, my.pause?)
```

VAL parameters must be passed *expressions* of the correct type. An expression could be a simple *variable* or *literal*.

Structured Processes (PROC instance)

```
PROC foo (VAL []BYTE s,
          VAL BOOL mode,
          INT result,
          CHAN INT in?, out!,
          CHAN BYTE pause?)
  ...
:
```



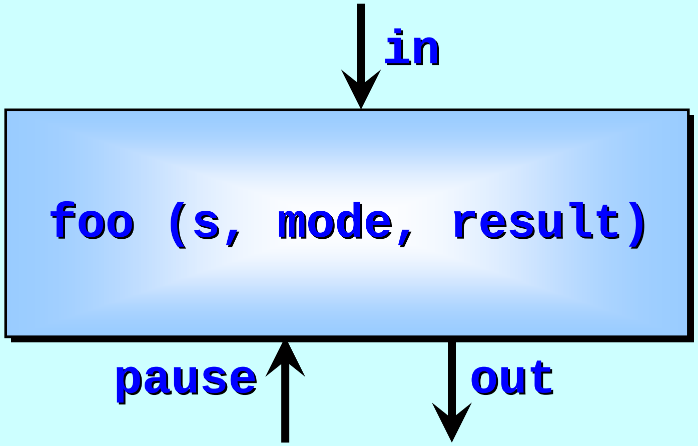
To create an instance, we must plug in correctly typed arguments – for example:

```
foo ("Goodbye World*c*n", TRUE, solution,
     q[i]?, q[i+1]!, my.pause?)
```

Reference parameters must be passed *variables* of the correct type. Changes to those parameters by the instanced process will be apparent in those *variables* when (if) the process instance terminates.

Structured Processes (PROC instance)

```
PROC foo (VAL []BYTE s,
          VAL BOOL mode,
          INT result,
          CHAN INT in?, out!,
          CHAN BYTE pause?)
  ...
:
```



To create an instance, we must plug in correctly typed arguments – for example:

```
foo ("Goodbye World*c*n", TRUE, solution,
     q[i]?, q[i+1]!, my.pause?)
```

Channel parameters must be passed the correct ends (**?** or **!**) of correctly typed *channels*.

Structured Processes (**PROC** instance)

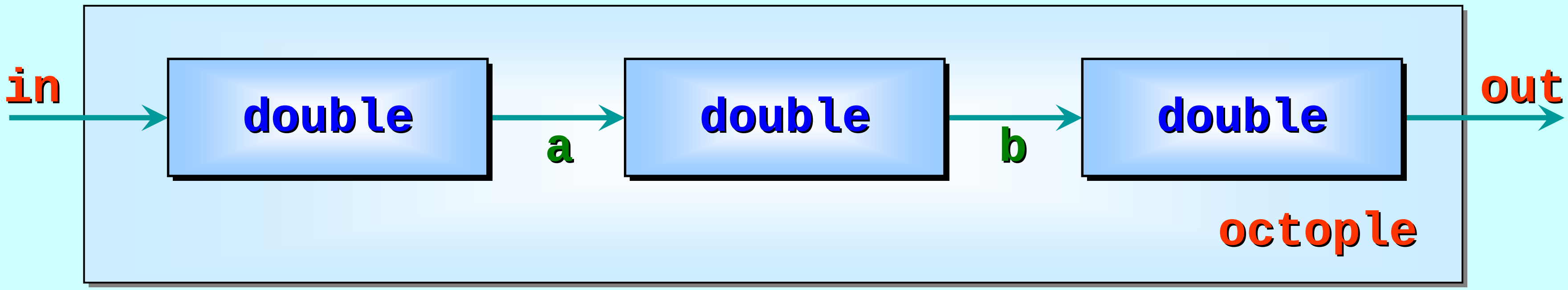
Process instances used in **SEQ**uence with other processes are sometimes referred to as *procedures*. For example:

```
INT answer:
SEQ
  out.string ("The answer is ", 0, screen!)
  ...  calculate answer
  out.int (answer, 0, screen!)
  out.string ("*c*n", 0, screen!)
```

The processes **`out.string`** and **`out.int`** are from the basic utilities library (**`"course.lib"`**) supporting this course. They output their given *string* (respectively *integer*) as ASCII text to their *channel* parameter and terminate. Their middle parameter is a minimum fieldwidth.

Structured Processes (PROC instance)

Process instances used in PARallel with other processes are are sometimes referred to as *components* (or just *processes*). For example:




```
PROC octople (CHAN INT in?, out!)
  CHAN INT a, b:
  PAR
    double (in?, a!)
    double (a?, b!)
    double (b?, out!)
:
```

This component scales by 8 the numbers flowing through it ...

Some occam-π Basics

Communicating processes ...

A flavour of occam-π …

Networks and communication …

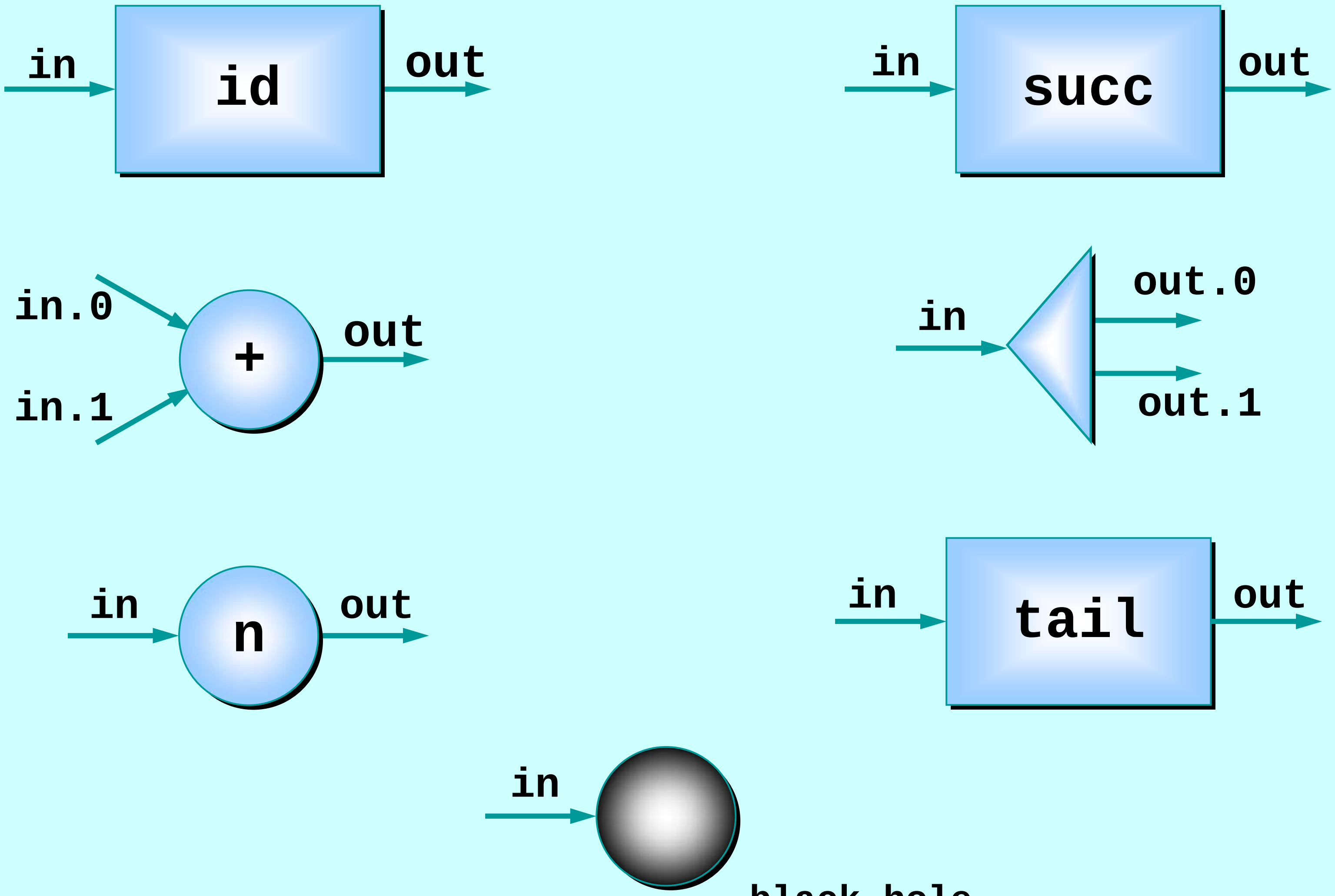
Types, channels, processes …

Primitive processes …

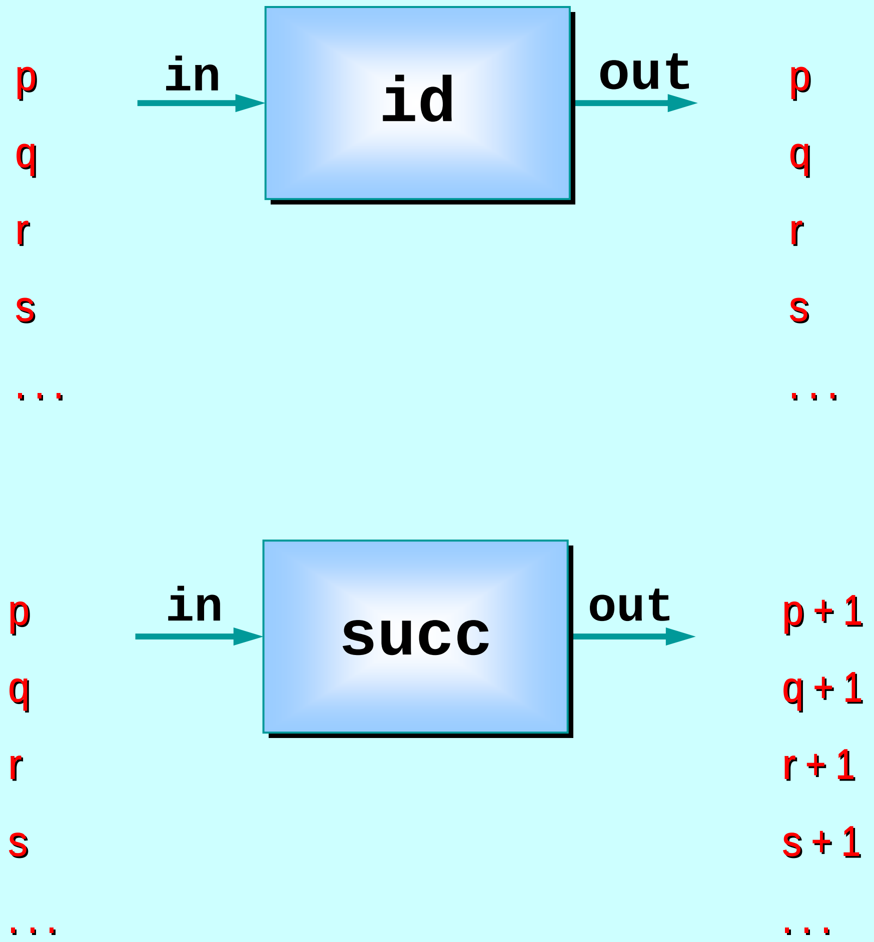
Structured processes …

‘Legoland’ …

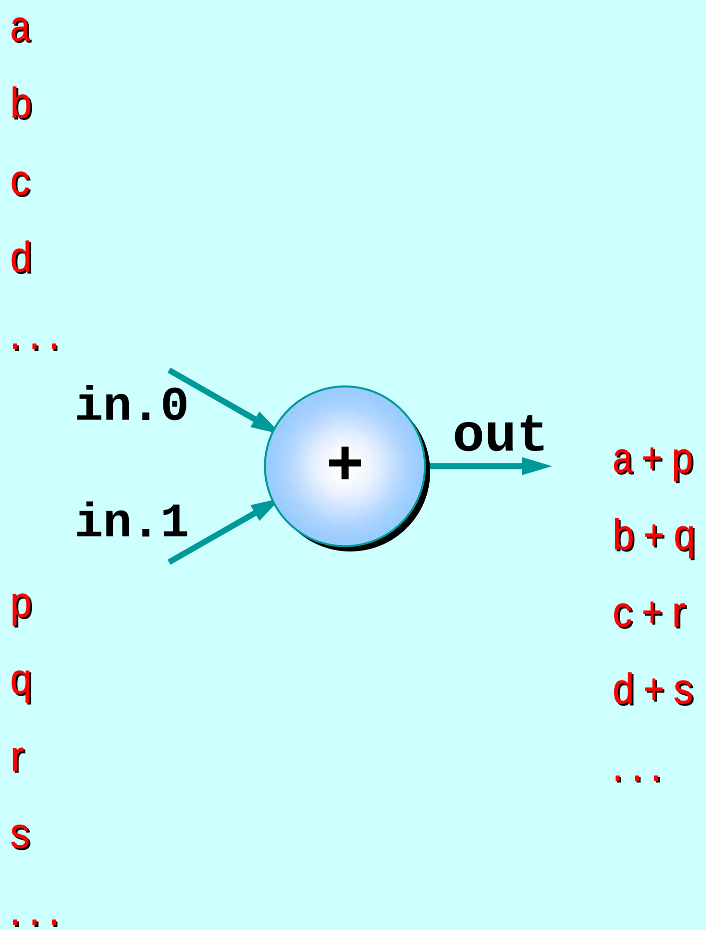
‘Legoland’ Catalog



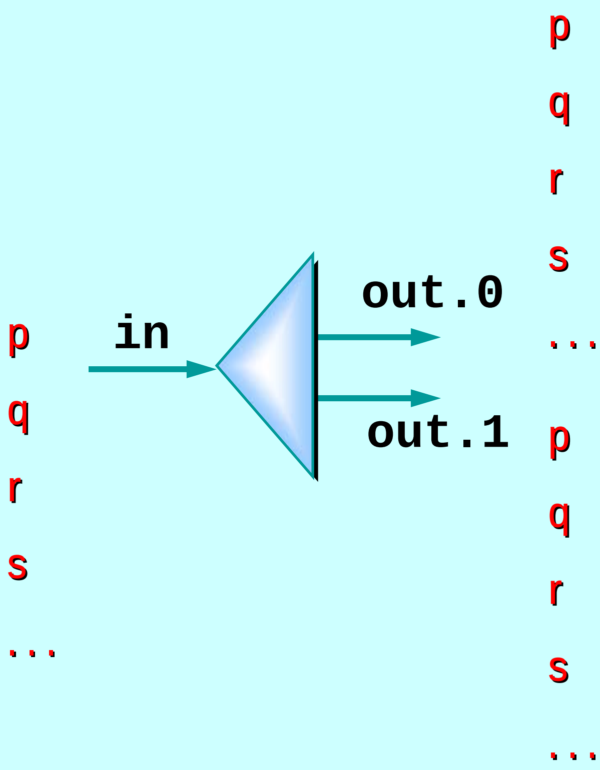
'Legoland' Catalog



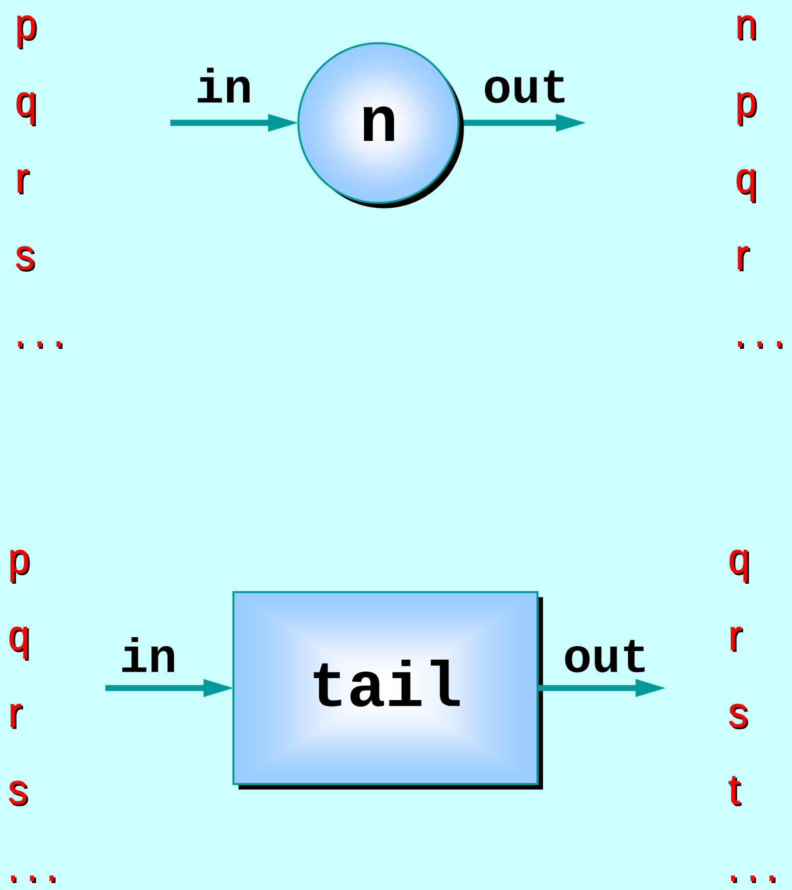
‘Legoland’ Catalog



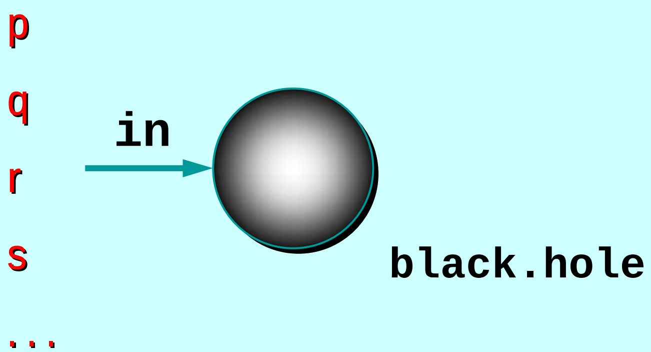
'Legoland' Catalog



‘Legoland’ Catalog



‘Legoland’ Catalog



‘Legoland’ Catalog

This is a catalog of fine-grained processes – think of them as pieces of hardware (e.g. chips).

They process data (**`INT`**s) flowing through them.

They are presented not because we suggest working at such fine levels of granularity …

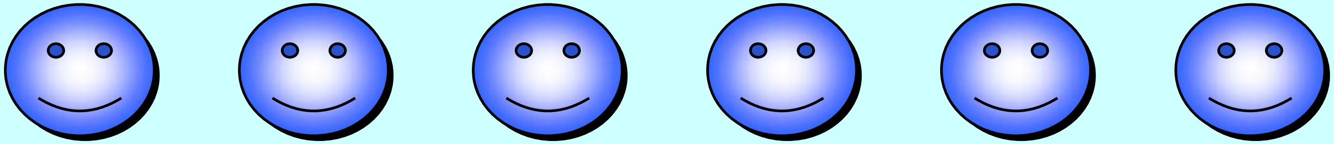
… they are presented in order to build up fluency in working with parallel logic.

‘Legoland’ Catalog

Parallel logic should become just as easy to manage as serial logic.

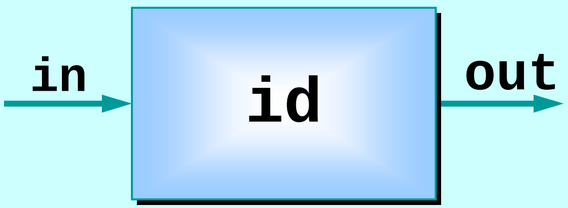
This is not the traditionally held view …

… but that tradition is ***wrong***.



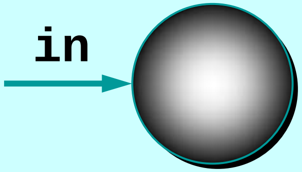
Let’s look at some **occam-π** code for these processes …

```
PROC id (CHAN INT in?, out!)
  WHILE TRUE
    INT x:
    SEQ
      in ? x
      out ! x
:
```

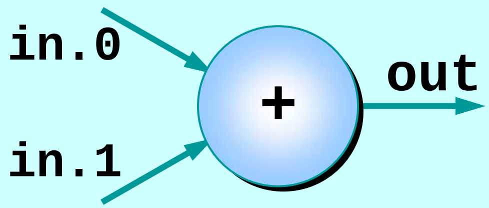



```
PROC succ (CHAN INT in?, out!)
  WHILE TRUE
    INT x:
    SEQ
      in ? x
      out ! x + 1
:
```


```
PROC black.hole (CHAN INT in?)
  WHILE TRUE
    INT x:
    in ? x
:
```

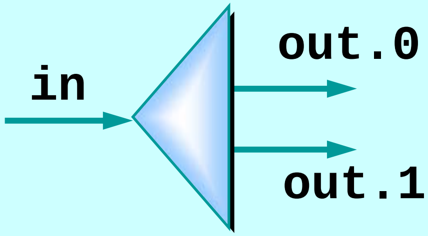


```
PROC plus (CHAN INT in.0?, in.1?, out!)
  WHILE TRUE
    INT x.0, x.1:
    SEQ
      PAR
        in.0 ? x.0
        in.1 ? x.1
      out ! x.0 + x.1
:
```



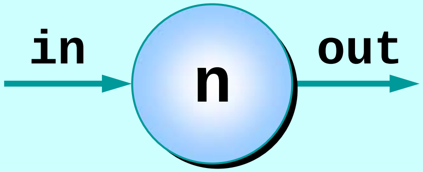
Note the parallel input …

```
PROC delta (CHAN INT in?, out.0!, out.1!)
  WHILE TRUE
    INT x:
    SEQ
      in ? x
      PAR
        out.0 ! x
        out.1 ! x
:
```



Note the parallel output …

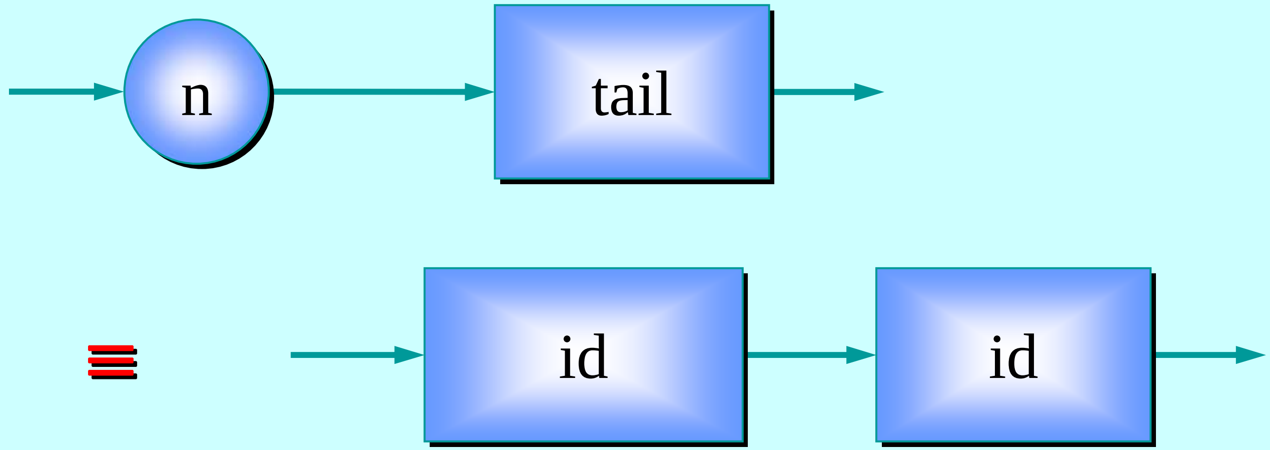
```
PROC prefix (VAL INT n,
             CHAN INT in?, out!)
  SEQ
    out ! n
    id (in, out)
:
```



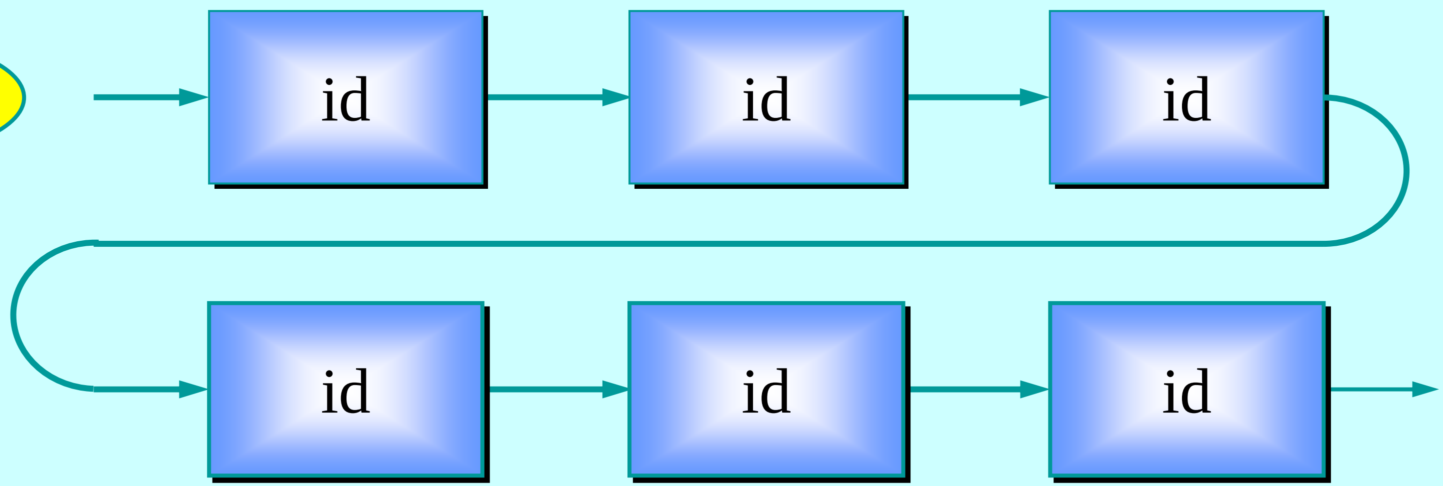

```
PROC tail (CHAN INT in?, out!)
  SEQ
    INT any:
    in ? any
    id (in, out)
:
```

scope of ‘**any**’

Theorem:



Theorem:



is a blocking *FIFO* buffer of capacity 6

Good News!

The good news is that we can ‘see’ this semantic equivalence with just one glance.

[CLAIM] ***CSP*** semantics cleanly reflects our intuitive feel for interacting systems.

This quickly builds up confidence …

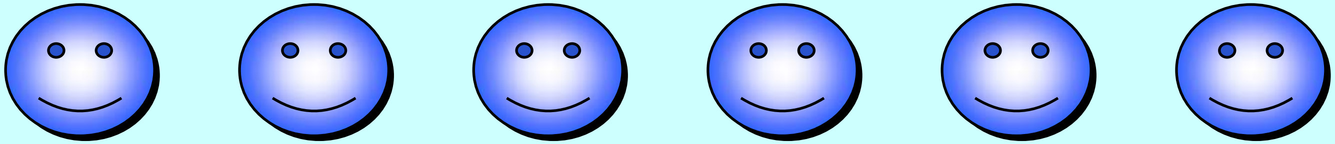
Wot - no chickens ?!!

Try ***Google***ing for this …

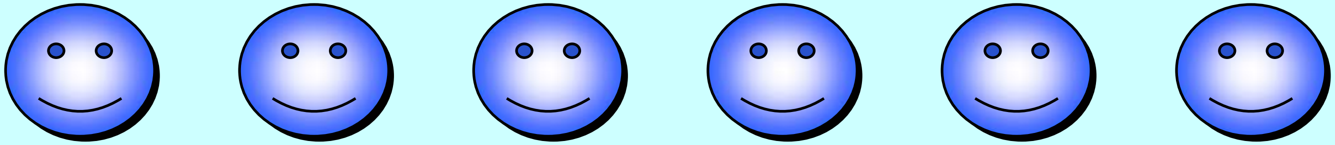
Good News!

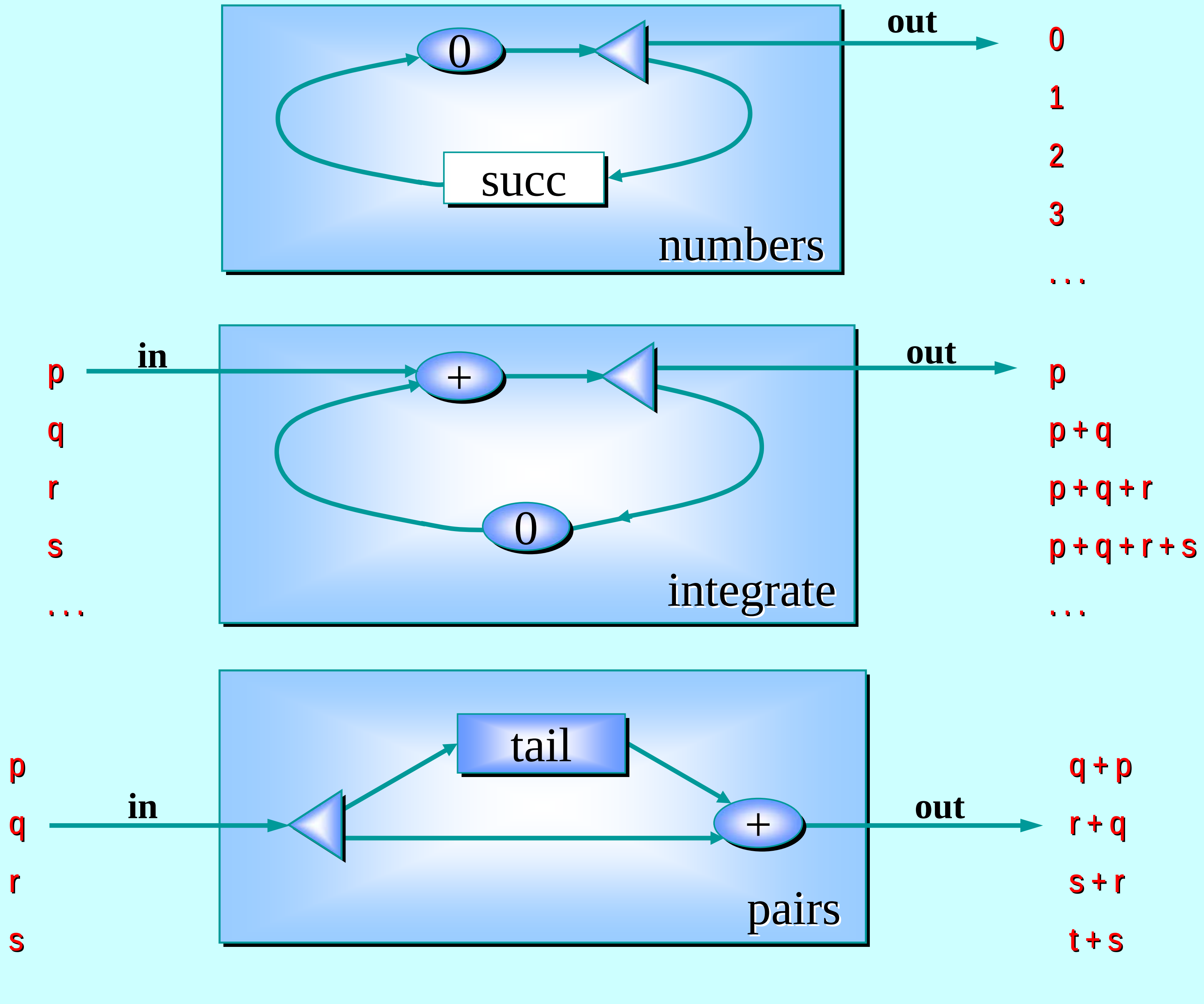
Let's build some simple circuits from these catalog components.

Can you see what they do … ?

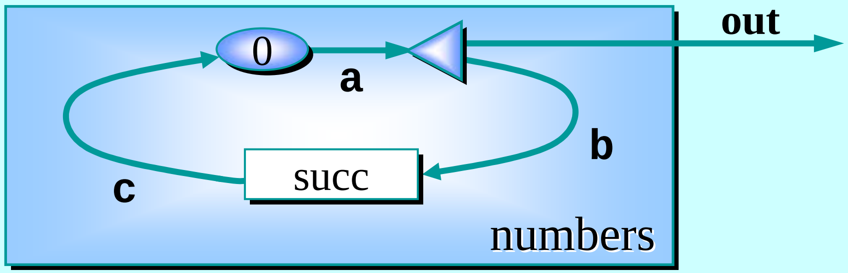


And how to describe them in **occam-π** … ?

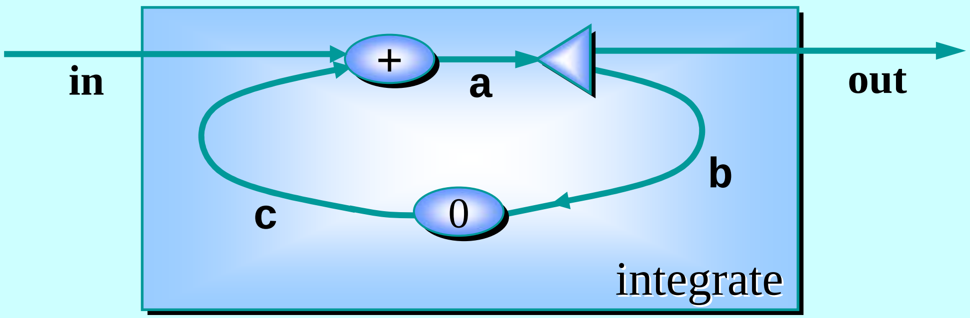



numbers
0
succ
out
0
1
2
3
. . .
integrate
in
+
0
out
p
q
r
s
. . .
p
p + q
p + q + r
p + q + r + s
. . .
pairs
tail
in
+
out
p
q
r
s
. . .
q + p
r + q
s + r
t + s
. . .

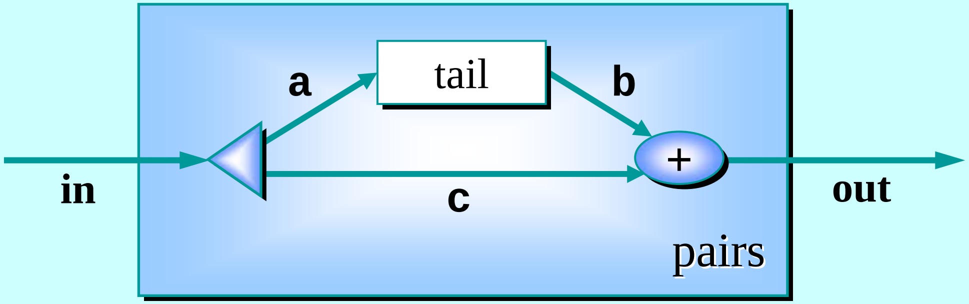
```
PROC numbers (CHAN INT out!)
  CHAN INT a, b, c:
  PAR
    delta (a?, out!, b!)
    succ (b?, c!)
    prefix (0, c?, a!)
:
```



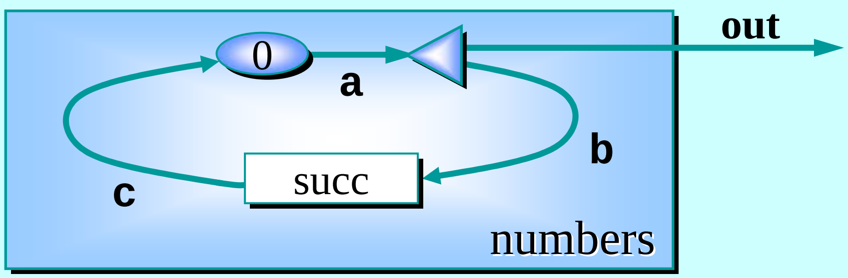

```
PROC integrate (CHAN INT in?, out!)
  CHAN INT a, b, c:
  PAR
    delta (a?, out!, b!)
    prefix (0, b?, c!)
    plus (in?, c?, a!)
:
```



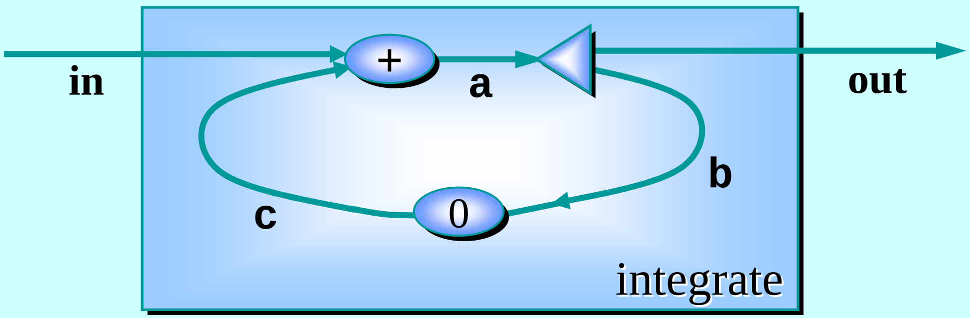

```
PROC pairs (CHAN INT in?, out!)
  CHAN INT a, b, c:
  PAR
    delta (in?, a!, c!)
    tail (a?, b!)
    plus (b?, c?, out!)
:
```



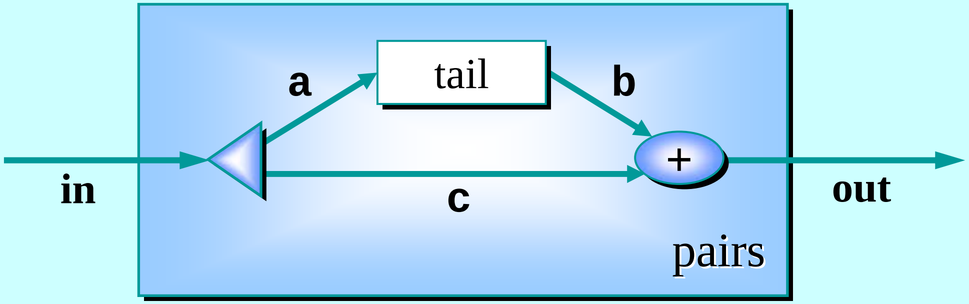
Note: this pushes numbers out so long as the receiver is willing to take it.



Note: this outputs one number for every input it gets.



Note: this needs two inputs before producing one output. Thereafter, it produces one number for every input it gets.



'Legoland' Catalog

Of course, these components also happen to have simple *sequential* implementations …

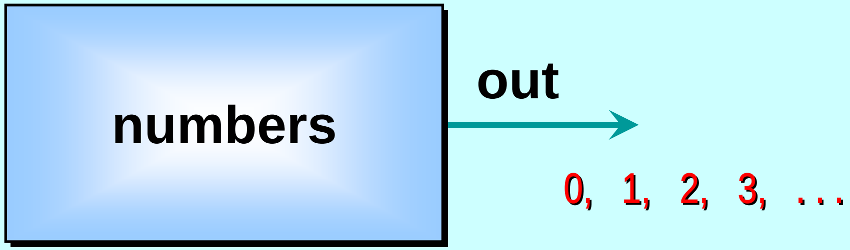
The *parallel* ones just shown were just to build fluency in CSP concurrency.

CSP (and **occam-π**) enables parallel and sequential logic to be built with equal ease.

In practice, sometimes parallel and sometimes sequential logic will be most appropriate – *just choose the simplest*.

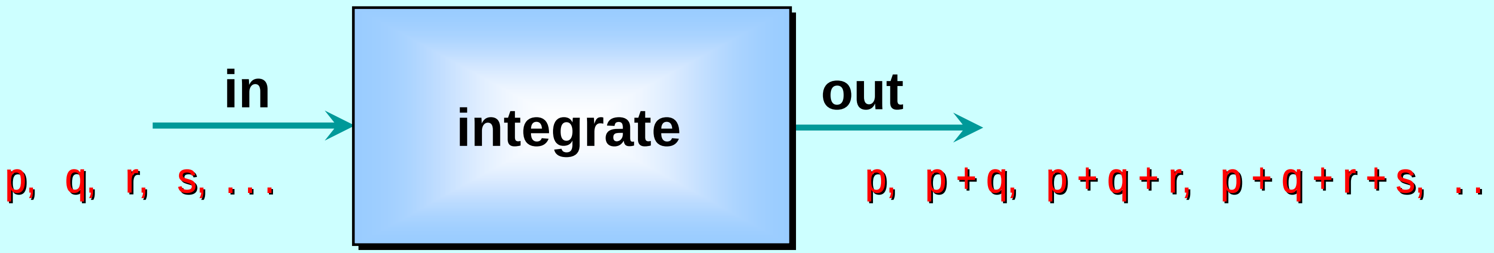
Parallel logic is not, *by nature*, especially difficult.

Sequential Version




```
PROC numbers (CHAN INT out!)
  INT n:
  SEQ
    n := 0
    WHILE TRUE
      SEQ
        out ! n
        n := n + 1
:
```

Sequential Version



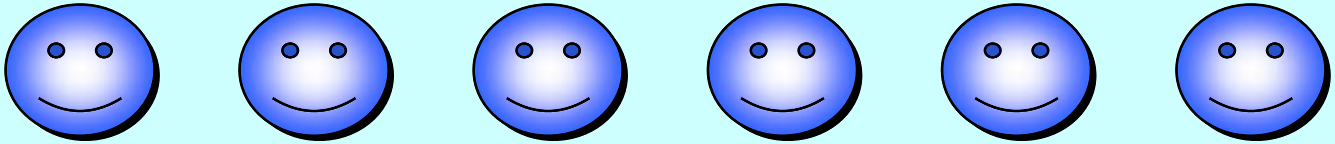

```
PROC integrate (CHAN INT in?, out!)
  INT total:
  SEQ
    total := 0
    WHILE TRUE
      INT x:
      SEQ
        in ? x
        total := total + x
        out ! total
:
```

Note: each declaration is as local as possible

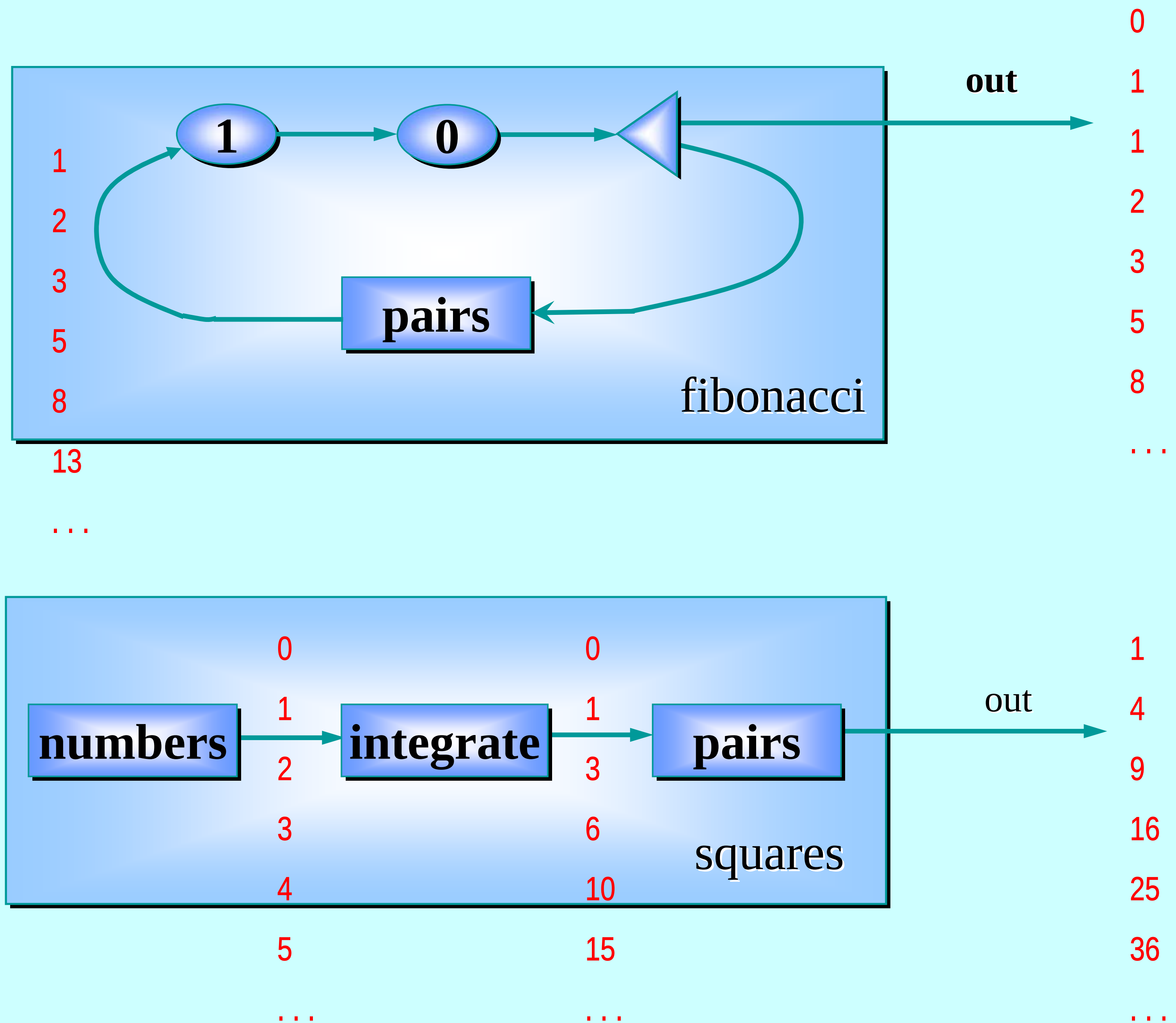
‘Legoland’ Catalog

Let’s build some more circuits from the components just constructed (either the sequential or parallel versions).

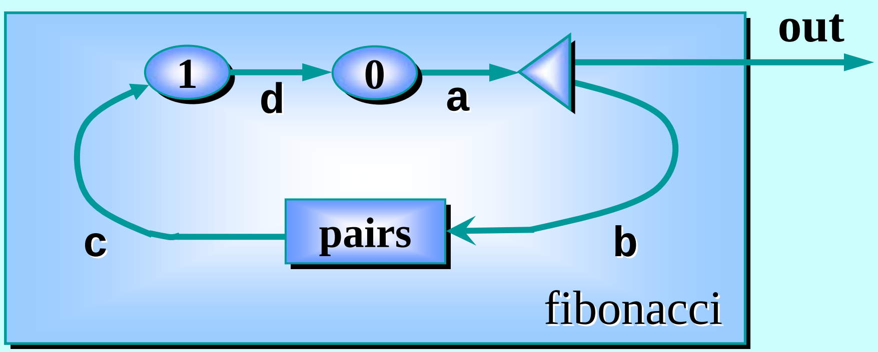
If we build using the parallel ones, we have *layered* networks – circuits within circuits.



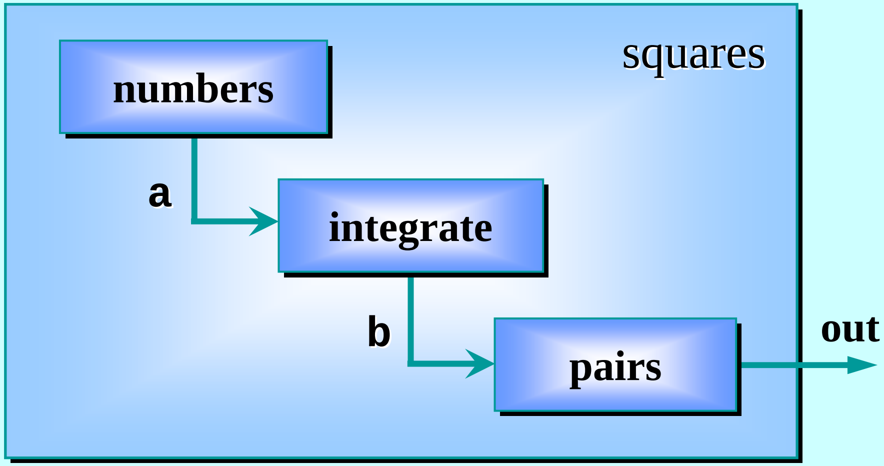
No problem!


out
1
0
pairs
fibonacci
0
1
1
2
3
5
8
. . .
1
2
3
5
8
13
. . .
numbers
integrate
pairs
squares
out
0
1
2
3
4
5
. . .
0
1
3
6
10
15
. . .
1
4
9
16
25
36
. . .

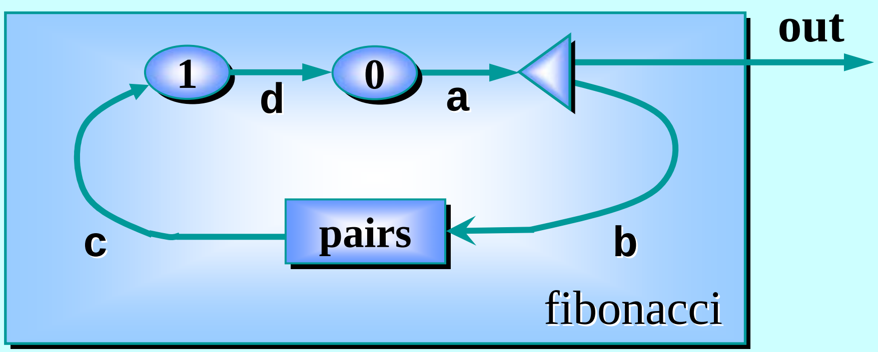
```
PROC fibonacci (CHAN INT out!)
  CHAN INT a, b, c, d:
  PAR
    delta (a?, b!, out!)
    pairs (b?, c!)
    prefix (0, d?, a!)
    prefix (1, c?, d!)
:
```




```
PROC squares (CHAN INT out!)
  CHAN INT a, b:
  PAR
    numbers (a!)
    integrate (a?, b!)
    pairs (b?, out!)
:
```

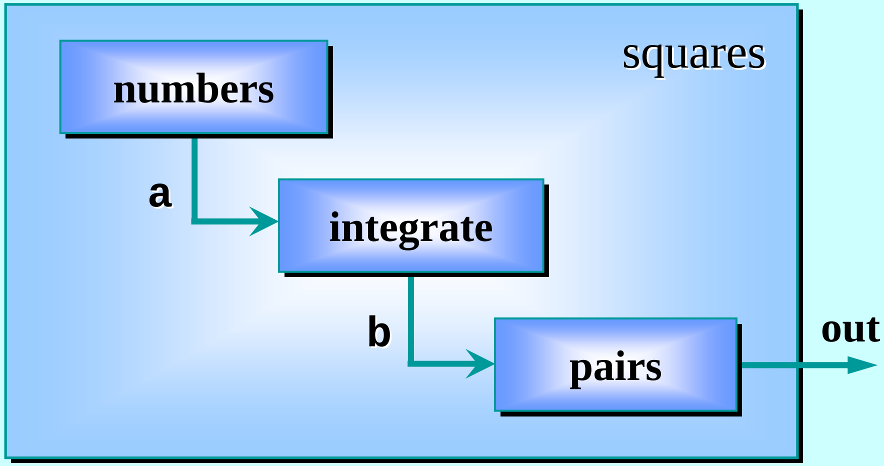


Note: the two numbers needed by **`PairsInt`** to get started are provided by the two **`PrefixInt`**s. Thereafter, only one number circulates on the feedback loop. If only one **`PrefixInt`** had been in the circuit, deadlock would have happened (with each process waiting trying to input).



Note: the traffic on individual channels:

```
<a>   = [0,  1,  1,  2,  3,  5,  8, 13, 21, ...]
<out> = [0,  1,  1,  2,  3,  5,  8, 13, 21, ...]
<b>   = [0,  1,  1,  2,  3,  5,  8, 13, 21, ...]
<c>   = [1,  2,  3,  5,  8, 13, 21, 34, 55, ...]
<d>   = [1,  1,  2,  3,  5,  8, 13, 21, 34, ...]
```



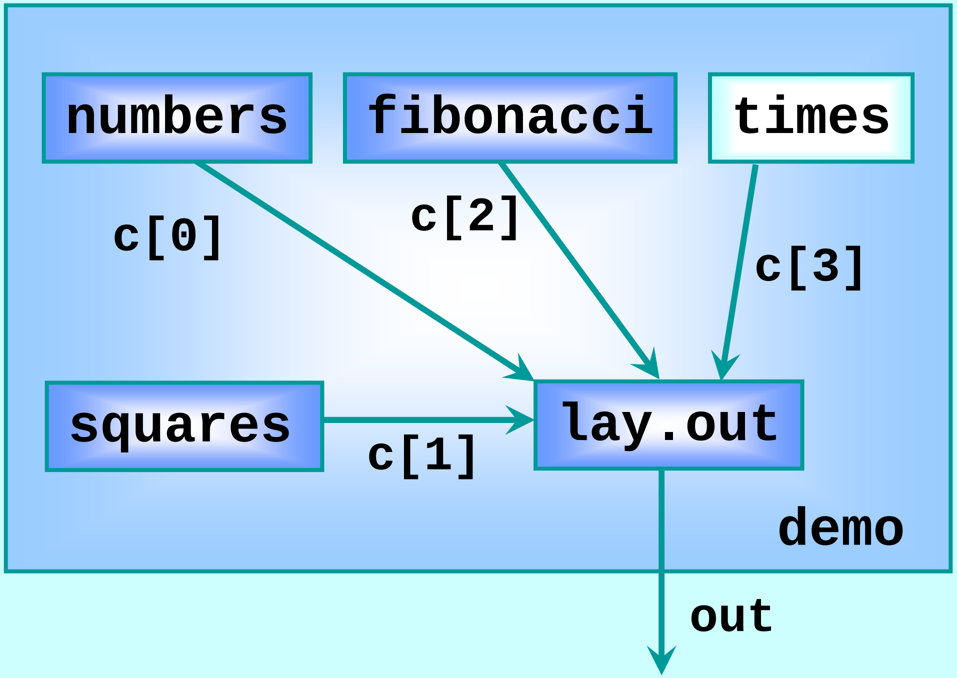
Note: the traffic on individual channels:

```
<a>   = [0,  1,  2,  3,  4,  5,  6,  7,  8, ...]
<b>   = [0,  1,  3,  6, 10, 15, 21, 28, 36, ...]
<out> = [1,  4,  9, 16, 25, 36, 49, 64, 81, ...]
```

Note: **use of channel array**

At this level, we have a network of 5 communicating processes.

```
PROC demo (CHAN BYTE out!)
  [4]CHAN INT c:
  PAR
    numbers(c[0]!)
    squares(c[1]!)
    fibonacci (c[2]!)
    times (c[3]!)
    lay.out (c?, out!)
:
```



In fact, 28 processes are involved: 18 non-terminating ones and 10 low-level transients (repeatedly starting up and shutting down for parallel input and output). *BUT we don't need to know that to reason at this level …* ☺ ☺ ☺

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    times (c[3]!)
    lay.out (c?, out!)
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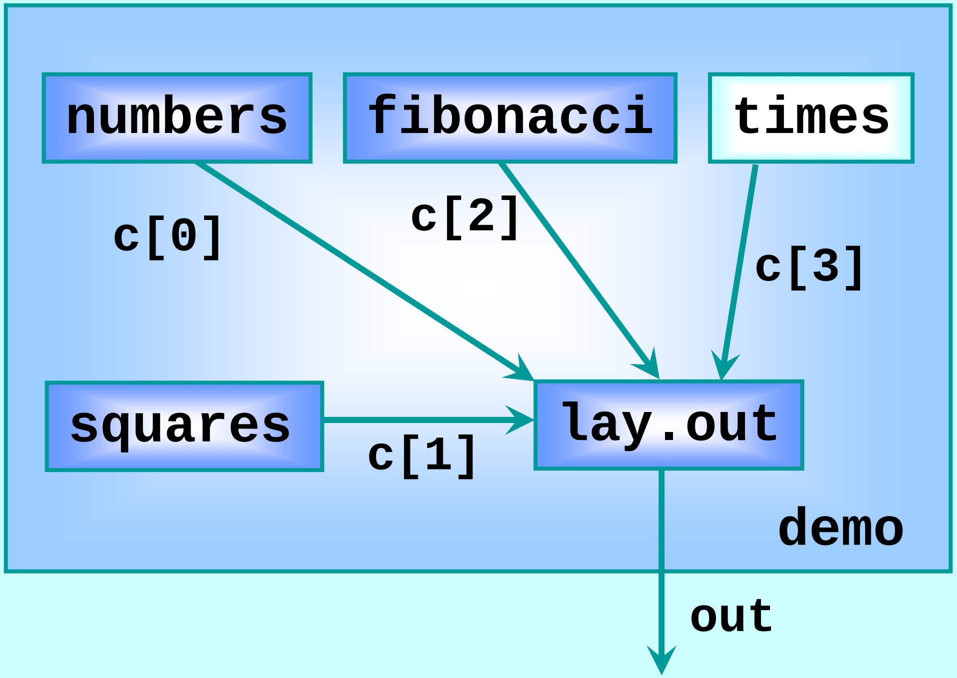
```



Fortunately, CSP semantics are compositional *– which means that we only have to reason at each layer of the network in order to design, understand, code, and maintain it.*