Automatic rate desynchronisation of reactive embedded systems

Paul CASPI, Alain GIRAULT, Xavier NICOLLIN, Daniel PILAUD, and Marc POUZET

INRIA Rhône-Alpes, INPG-VERIMAG, and Orsay/LRI

Grenoble and Paris, FRANCE

Introduction

Embedded reactive programs

- embedded so they have limited resources
- reactive so they react continuously with their environment

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- reactive so they react continuously with their environment

We consider programs whose control structure is a finite state automaton

Put inside a periodic execution loop:

```
loop each tick
  read inputs
  compute next state
  write outputs
end loop
```

Automatic rate desynchronisation

Desynchronisation: to transform one centralised synchronous program into a GALS program

➪ Each local program is embedded inside its own periodic execution loop

Automatic: the user only provides distribution specifications

Rate desynchronisation:

- the periods of the execution loops will not be the same and
- not necessarily identical to the period of the initial centralised program

Motivation: long duration tasks

Characteristics:

- Their execution time is long
- Their execution time is known and bounded
- Their maximal execution rate is known and bounded

Examples:

- The CO3N4 nuclear plant control system of Schneider Electric
- The Mars rover pathfinder

A small example

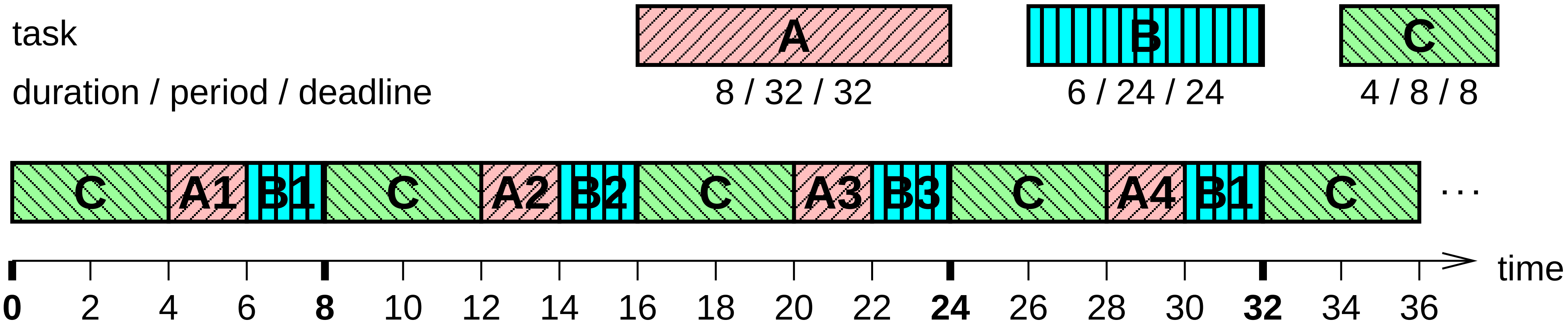
Consider a system with three independant tasks:

- Task A performs slow computations:
  ➪ duration = 8, period = deadline = 32
- Task B performs medium and not urgent computations:
  ➪ duration = 6, period = deadline = 24
- Task C performs fast and urgent computations:
  ➪ duration = 4, period = deadline = 8

How to implement this system?

Manual task slicing

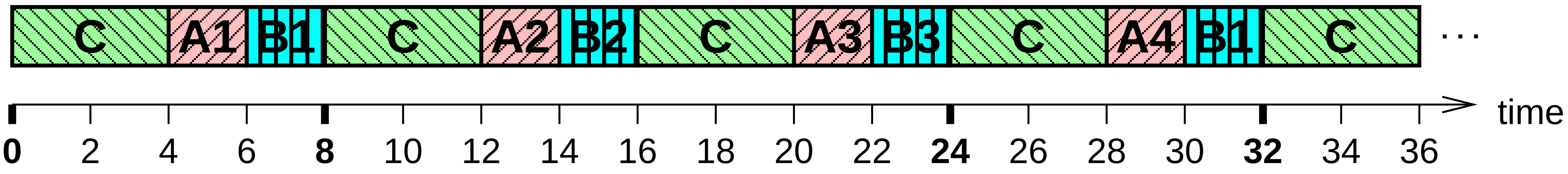
Tasks A and B are sliced into small chunks, which are interleaved with task C



Manual task slicing

Tasks A and B are sliced into small chunks, which are interleaved with task C

task	A	B	C
duration / period / deadline	8 / 32 / 32	6 / 24 / 24	4 / 8 / 8



Very hard and error prone because:

- The slicing is complex
- The implementation must be correct and deadlock-free

Manually programming 3 async. tasks

Tasks A, B, and C are performed by one process each

The task slicing is done by the scheduler of the underlying RTOS

But the manual programming is difficult

Example: the Mars Rover Pathfinder had priority inversion!

Automatic distribution

The user programs a centralised system

The centralised program is compiled, debugged, and validated

It is then automatically distributed into three processes

The correctness ensures that the obtained distributed system is functionnally equivalent to the centralised one

Example: the `FILTER` program

```
state 0:
go(CK,IN)
if (CK) then
    RES:=0
    write(RES)
    V:=0
    OUT:=SLOW(IN)
    write(OUT)
    goto 1
else
    RES:=V
    write(RES)
    goto 0
endif
```

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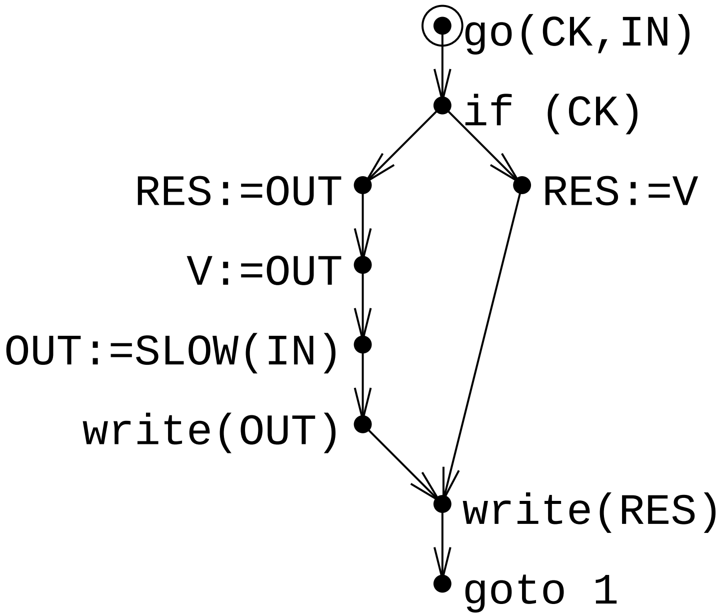

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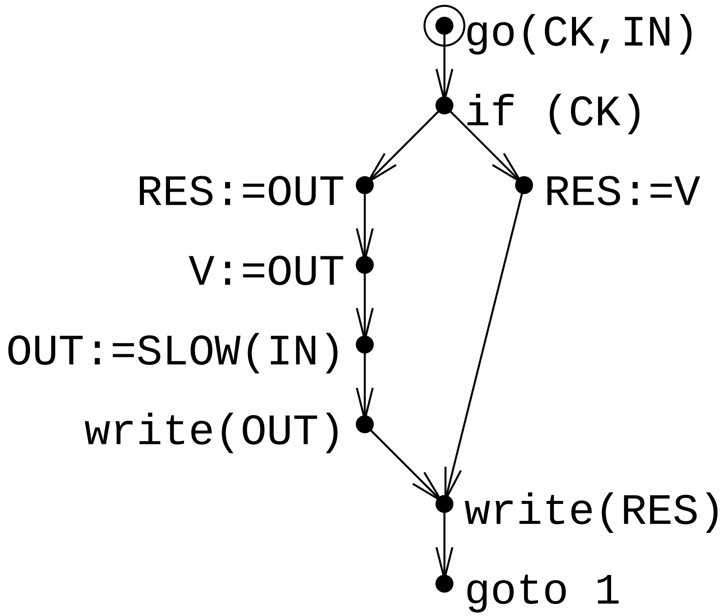

go(CK,IN)

if (CK)

RES:=OUT

RES:=V

V:=OUT

OUT:=SLOW(IN)

write(OUT)

write(RES)

goto 1

- It has two inputs (the Boolean `CK` and the integer `IN`) and two outputs (the integers `RES` and `OUT`)

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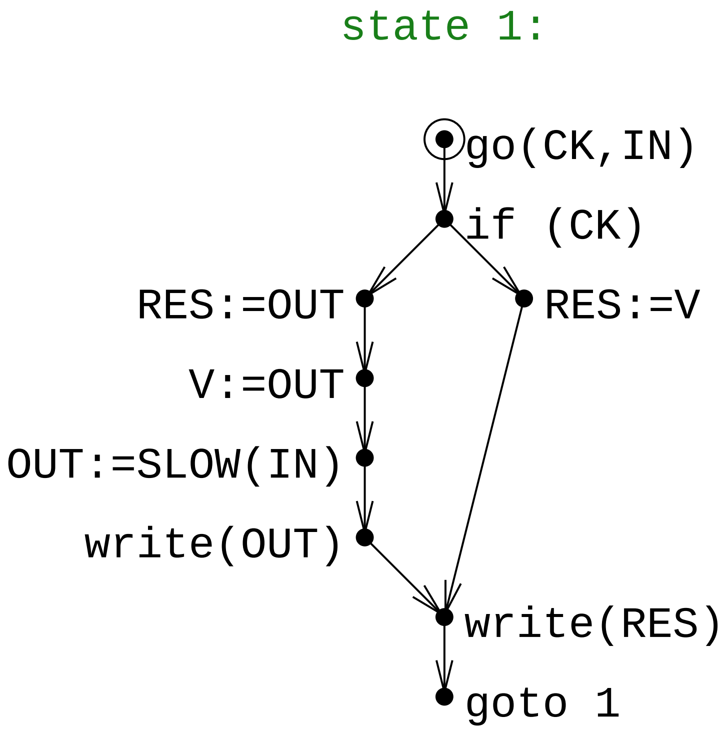


- It has two inputs (the Boolean `CK` and the integer `IN`) and two outputs (the integers `RES` and `OUT`)
- The `go(CK,IN)` action materialises the `read input` phase

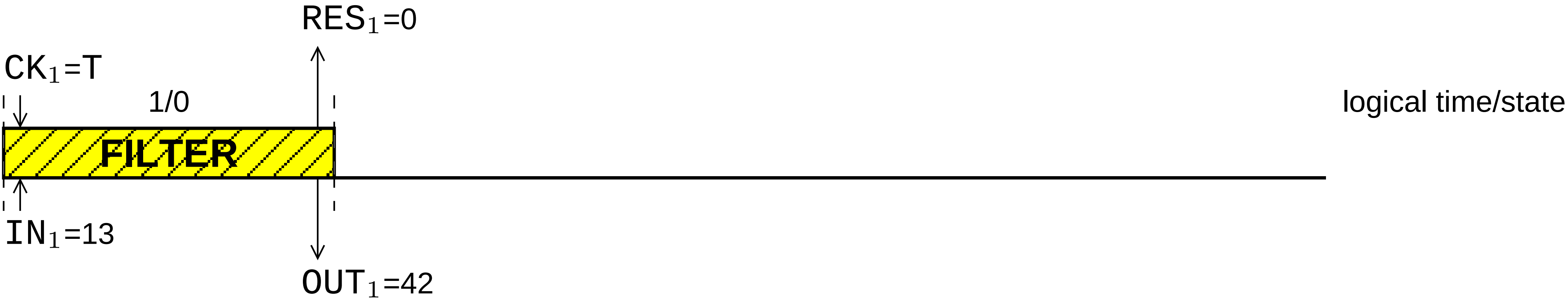
Rates

The `FILTER` program has two inputs (the Boolean `CK` and the integer `IN`) and two outputs (the integers `RES` and `SLOW`)

Each input and output has a rate, which is the sequence of logical instants where it exists

- `IN` is used only when `CK` is `true`, so its rate is `CK`
- `CK` is used at each cycle, so its rate is the base rate
- `OUT` is computed each time `CK` is `true`, so its rate is `CK`
- `RES` is computed at each cycle, so its rate is the base rate

A run of the centralised `FILTER`



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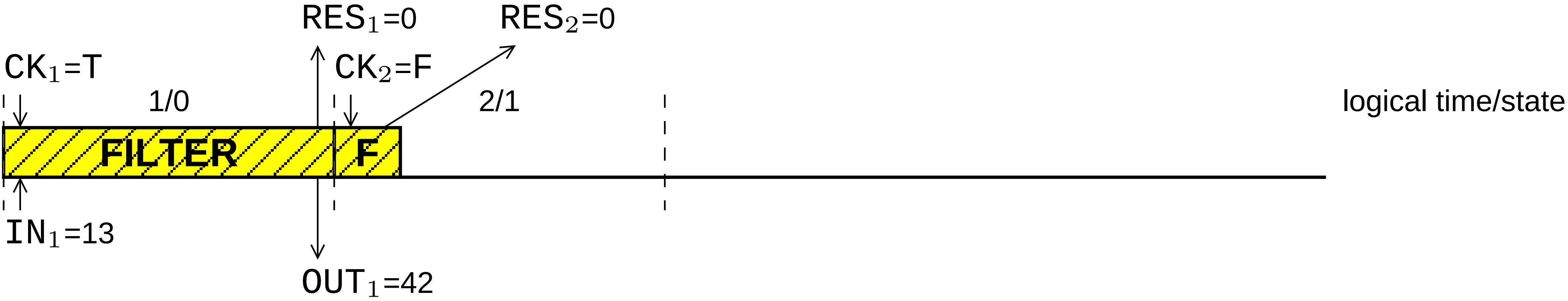

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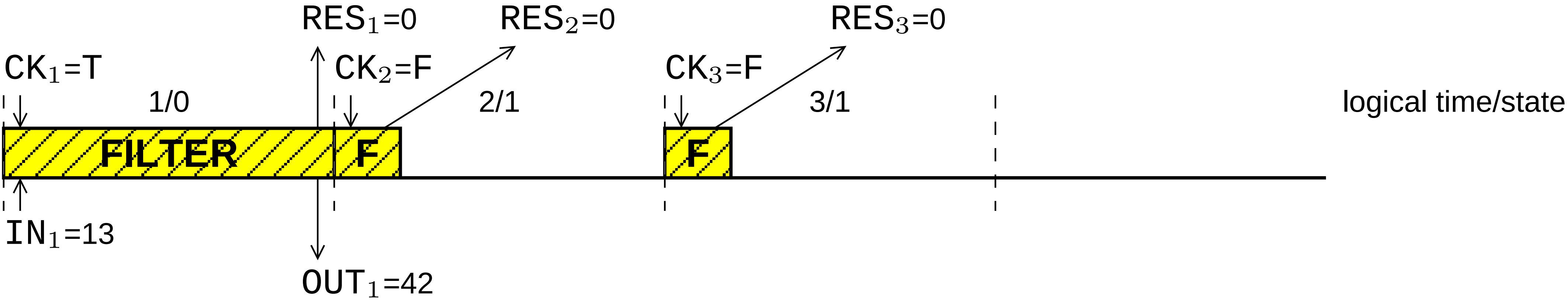

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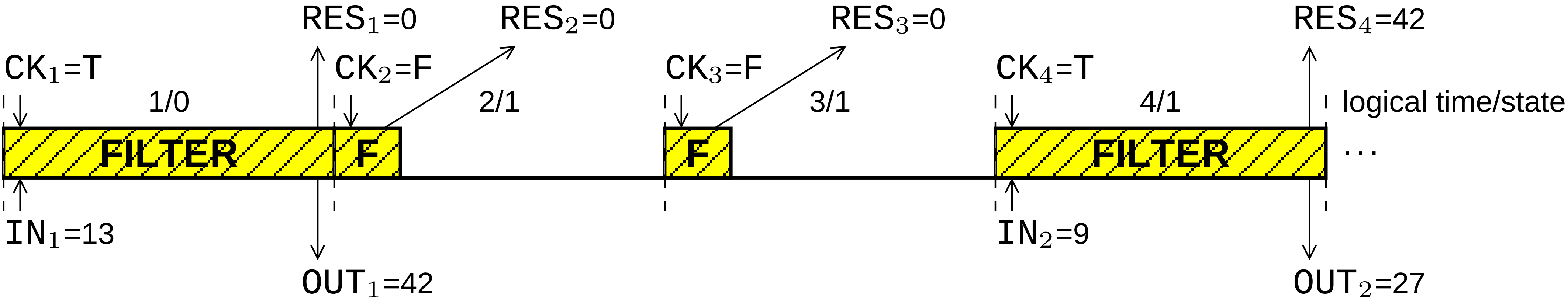

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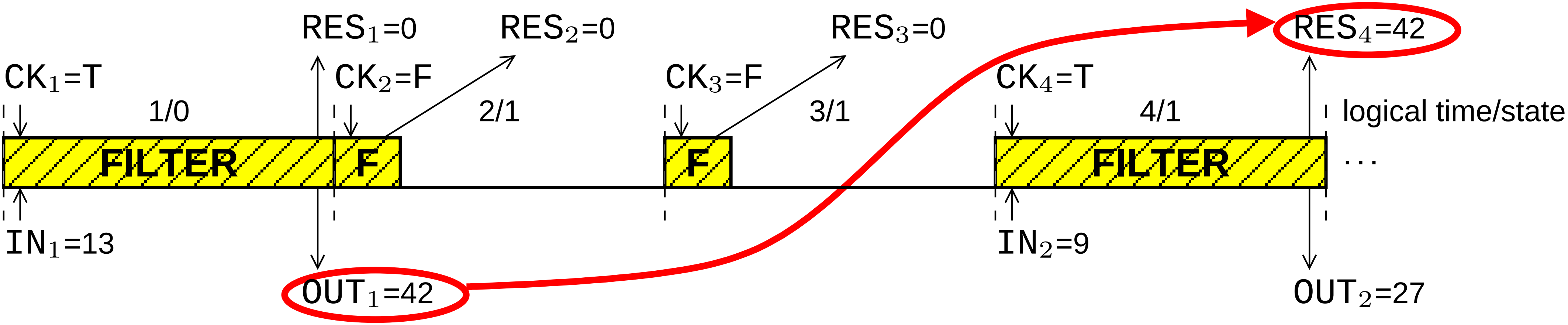

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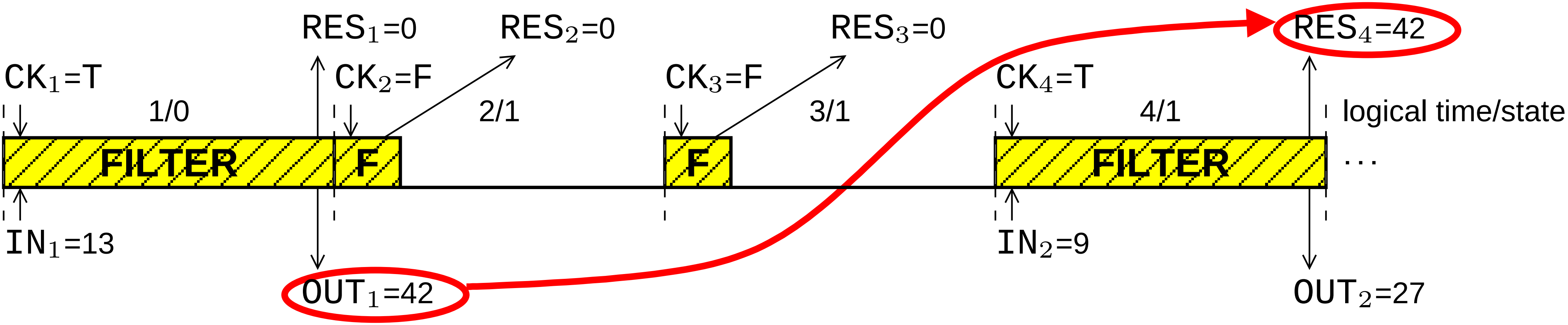
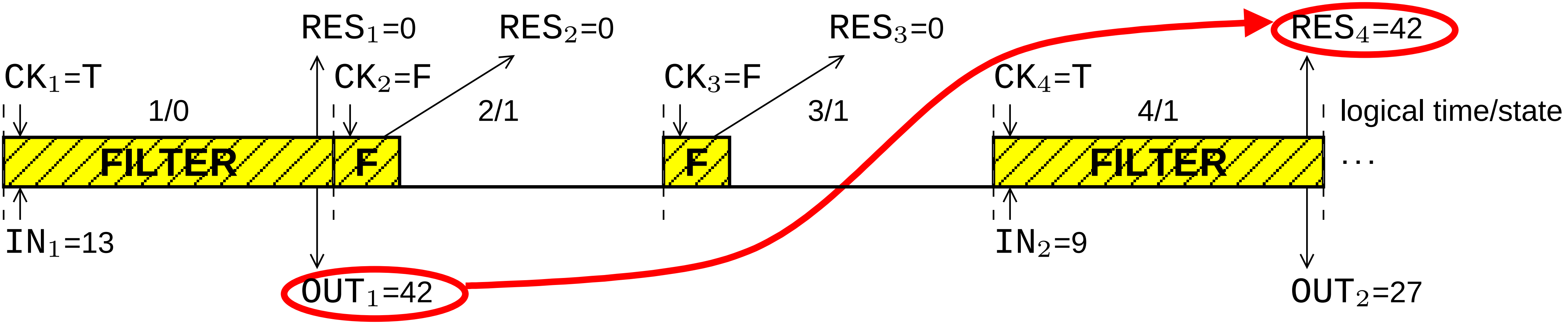


$$\left.\begin{array}{ll}\text{WCET}(\texttt{SLOW}) & = 7\\ \text{WCET(other computations)} & = 1\end{array}\right\} \Longrightarrow \text{WCET}(\texttt{FILTER}) = 8$$

Thus the period of the execution loop (base rate)

must be greater than 8

Where are we going?



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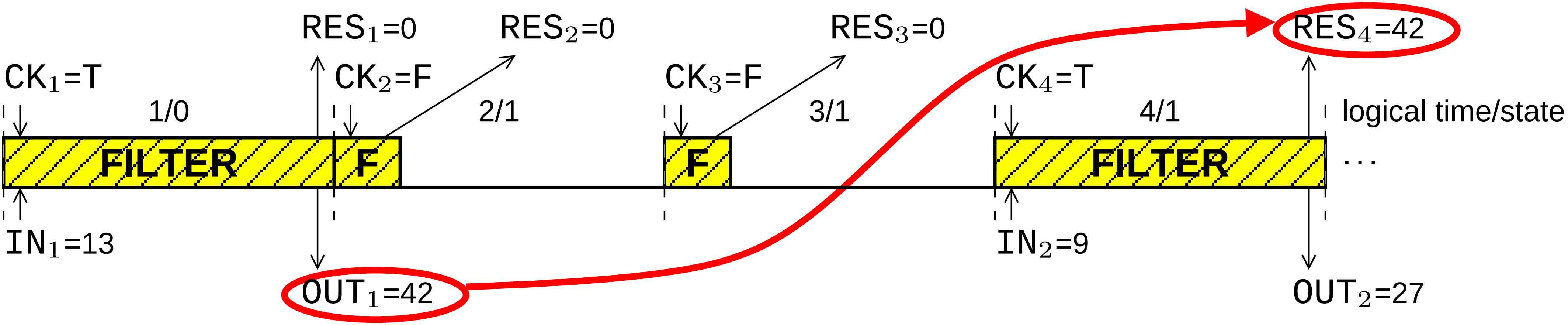
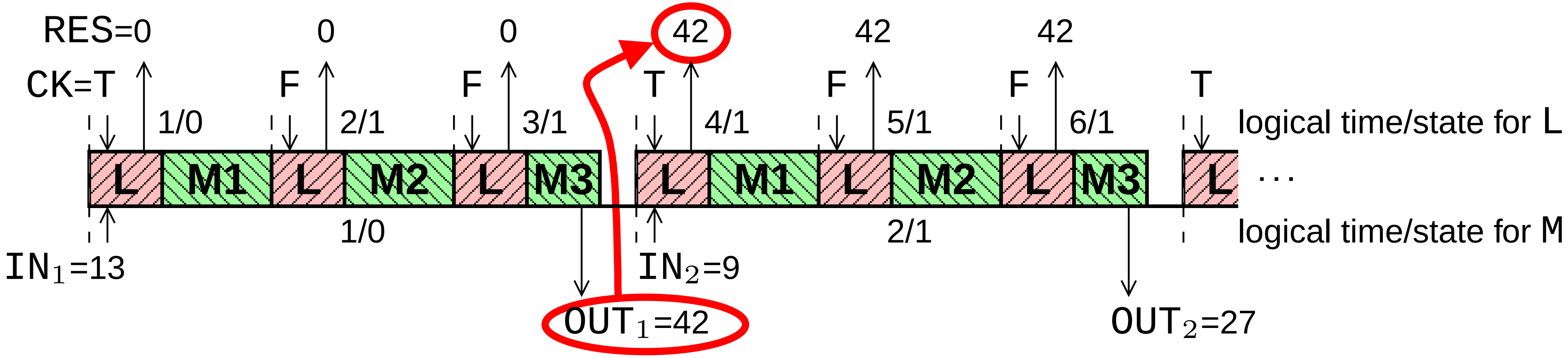


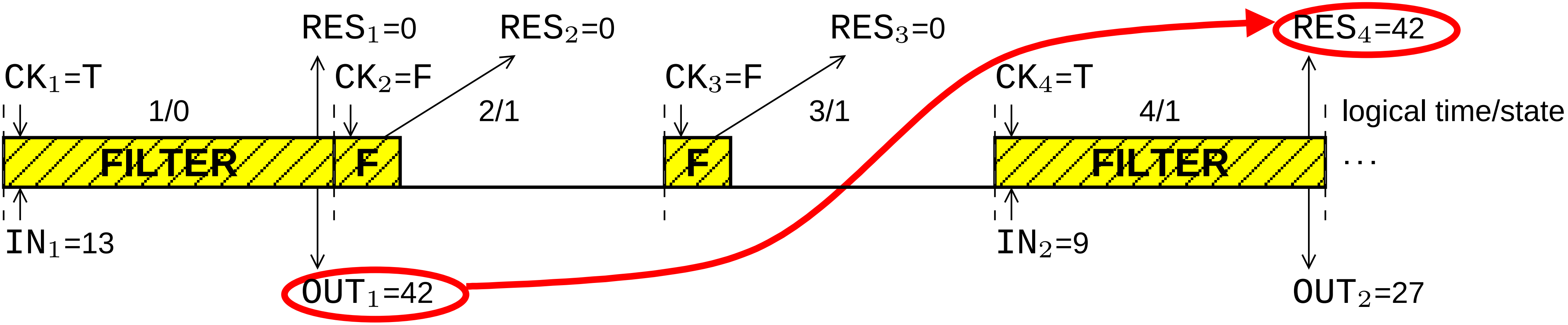
Two tasks running on a single processor:



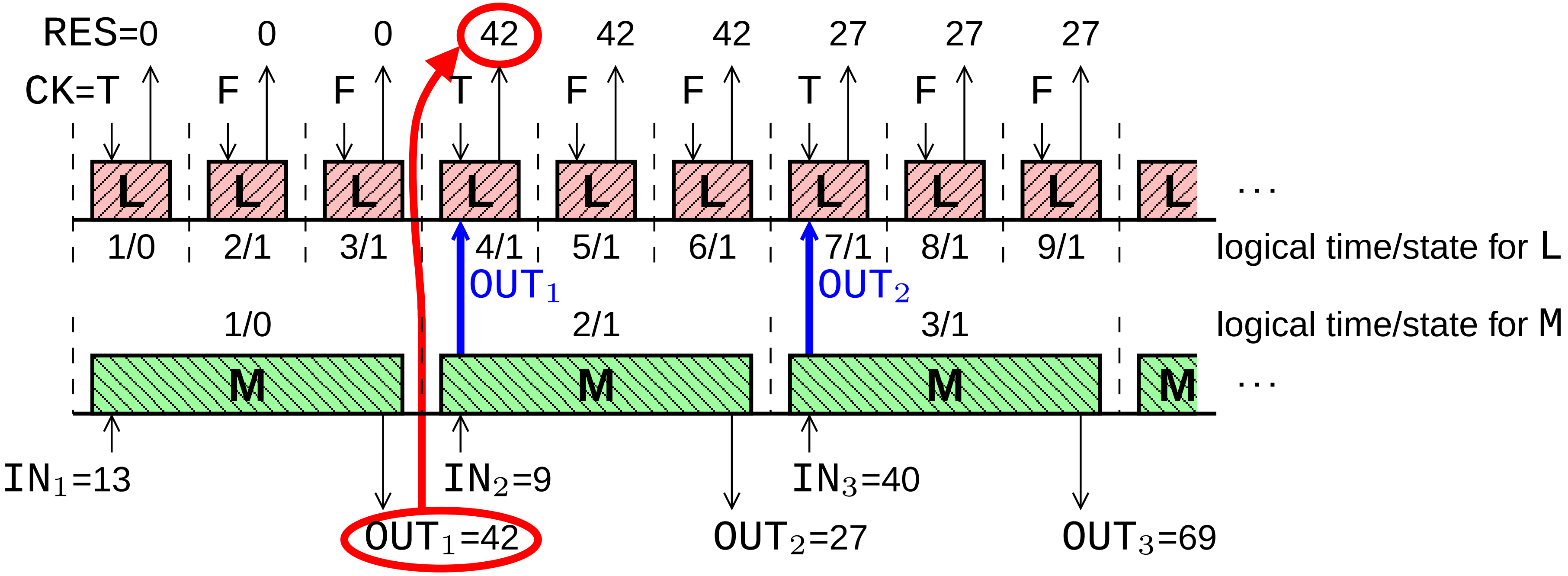
Task L performs the fast computations

Task M performs the slow computations, sliced into 3 chunks

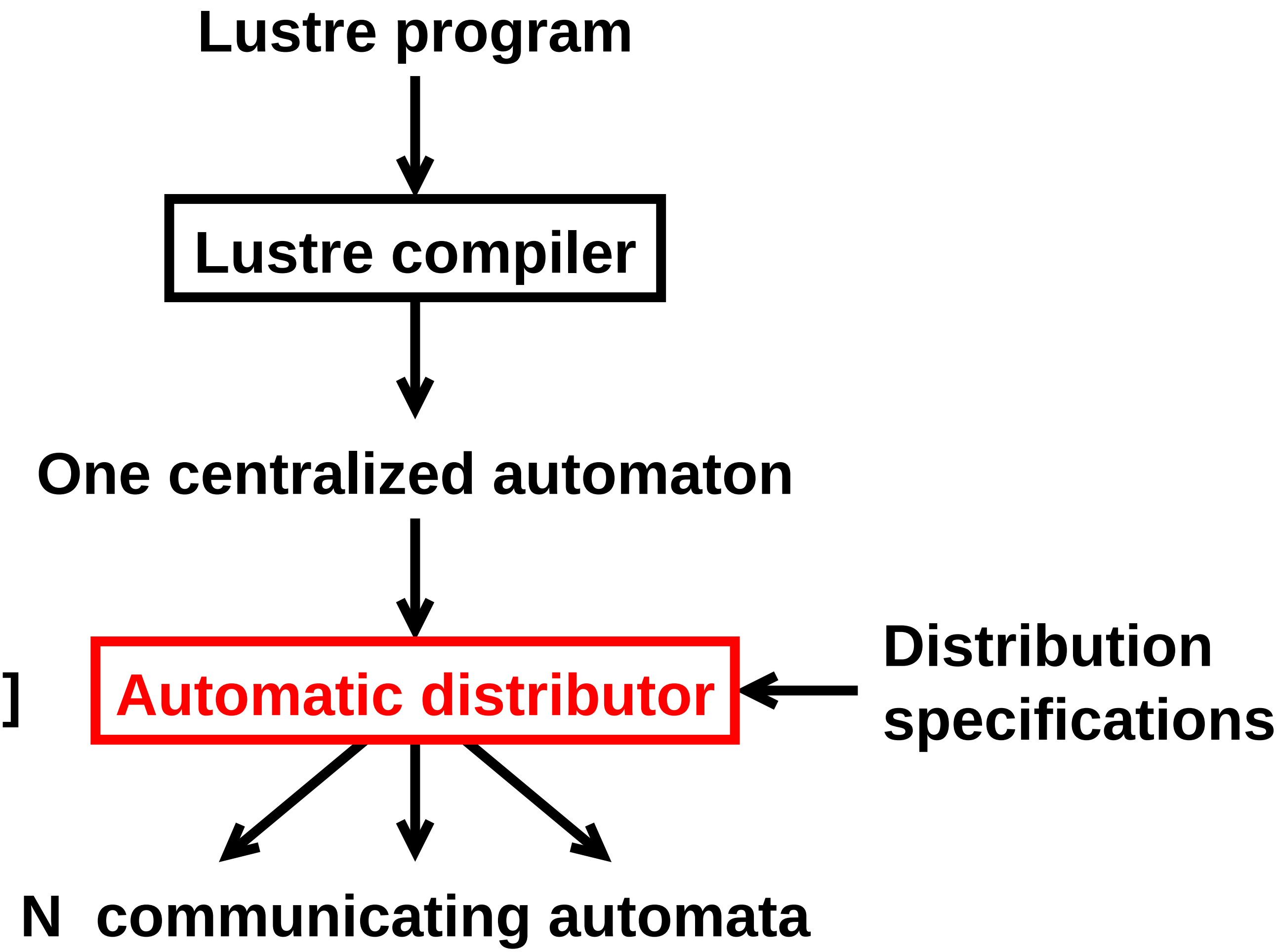
Where are we going?


RES$_1$=0 RES$_2$=0 RES$_3$=0 RES$_4$=42
CK$_1$=T CK$_2$=F CK$_3$=F CK$_4$=T
1/0 2/1 3/1 4/1 logical time/state
FILTER F F FILTER . . .
IN$_1$=13 IN$_2$=9
OUT$_1$=42 OUT$_2$=27

Two tasks running on two processors:


RES=0 0 0 42 42 42 27 27 27
CK=T F F T F F T F F
L L L L L L L L L L . . .
1/0 2/1 3/1 4/1 5/1 6/1 7/1 8/1 9/1 logical time/state for L
OUT$_1$ OUT$_2$
1/0 2/1 3/1 logical time/state for M
M M M M . . .
IN$_1$=13 IN$_2$=9 IN$_3$=40
OUT$_1$=42 OUT$_2$=27 OUT$_3$=69

Our automatic distribution algorithm



Lustre program

Lustre compiler

One centralized automaton

[Caspi, Girault & Pilaud 1999]

Automatic distributor

Distribution specifications

N communicating automata

(one automaton for each computing location)

Communication primitives

Two FIFO channels for each pair of locations, one in each direction:

- `send(dst,var)` inserts the value of variable `var` into the queue directed towards location `dst`

  Non blocking

- `var:=receive(src)` extracts the head value from the queue starting at location `src` and assigns it to variable `var`

  Blocking when the queue is empty

Distribution specifications

location name	assigned rates
`L`	base
`M`	`CK`

This part is given by the user

Distribution specifications

location name	assigned rates	infered inputs & outputs
`L`	base	`CK`, `RES`
`M`	`CK`	`IN`, `OUT`

The infered inputs and outputs are those whose rate matches the assigned rate

base {`RES`, `CK`}
↓
`CK` {`IN`, `OUT`}

Distribution specifications

location name	assigned rates	infered inputs & outputs	infered location rate
`L`	base	`CK`, `RES`	base
`M`	`CK`	`IN`, `OUT`	`CK`

The infered rate is the root of the smallest subtree containing all the rates assigned by the user

First attempt of distribution

```
state 0
go(CK,IN)

if (CK) then

   RES:=OUT
   V:=OUT
   OUT:=SLOW(IN)
   write(OUT)
else
   RES:=V
endif
write(RES)
goto 1
```

First attempt of distribution

```
state 0 -- location L
go(CK,IN)

if (CK) then

   RES:=OUT
   V:=OUT
   OUT:=SLOW(IN)
   write(OUT)
else
   RES:=V
endif
write(RES)
goto 1
```

```
state 0 -- location M
go(CK,IN)

if (CK) then

   RES:=OUT
   V:=OUT
   OUT:=SLOW(IN)
   write(OUT)
else
   RES:=V
endif
write(RES)
goto 1
```

First attempt of distribution

```
state 0 -- location L           state 0 -- location M
go(CK)                          go(IN)

if (CK) then                    if (CK) then

   RES:=OUT
   V:=OUT
                                   OUT:=SLOW(IN)
                                   write(OUT)
else                            else
   RES:=V
endif                           endif
write(RES)
goto 1                          goto 1
```

First attempt of distribution

```
state 0 -- location L
go(CK)
send(M,CK)
if (CK) then
   OUT:=receive(M)
   RES:=OUT
   V:=OUT


else
   RES:=V
endif
write(RES)
goto 1
```

```
state 0 -- location M
go(IN)
CK:=receive(L)
if (CK) then
   send(L,OUT)


   OUT:=SLOW(IN)
   write(OUT)
else

endif

goto 1
```

First attempt of distribution

location `L` (rate `base`)

```
state 0:
go(CK)
send(M,CK)
if (CK) then {
  RES:=0
  write(RES)
  V:=0
  goto 1
} else {
  RES:=V
  write(RES)
  goto 0
} endif
```

```
state 1:
go(CK)
send(M,CK)
if (CK) then {
  OUT:=receive(M)
  RES:=OUT
  V:=OUT
} else {
  RES:=V
} endif
write(RES)
goto 1
```

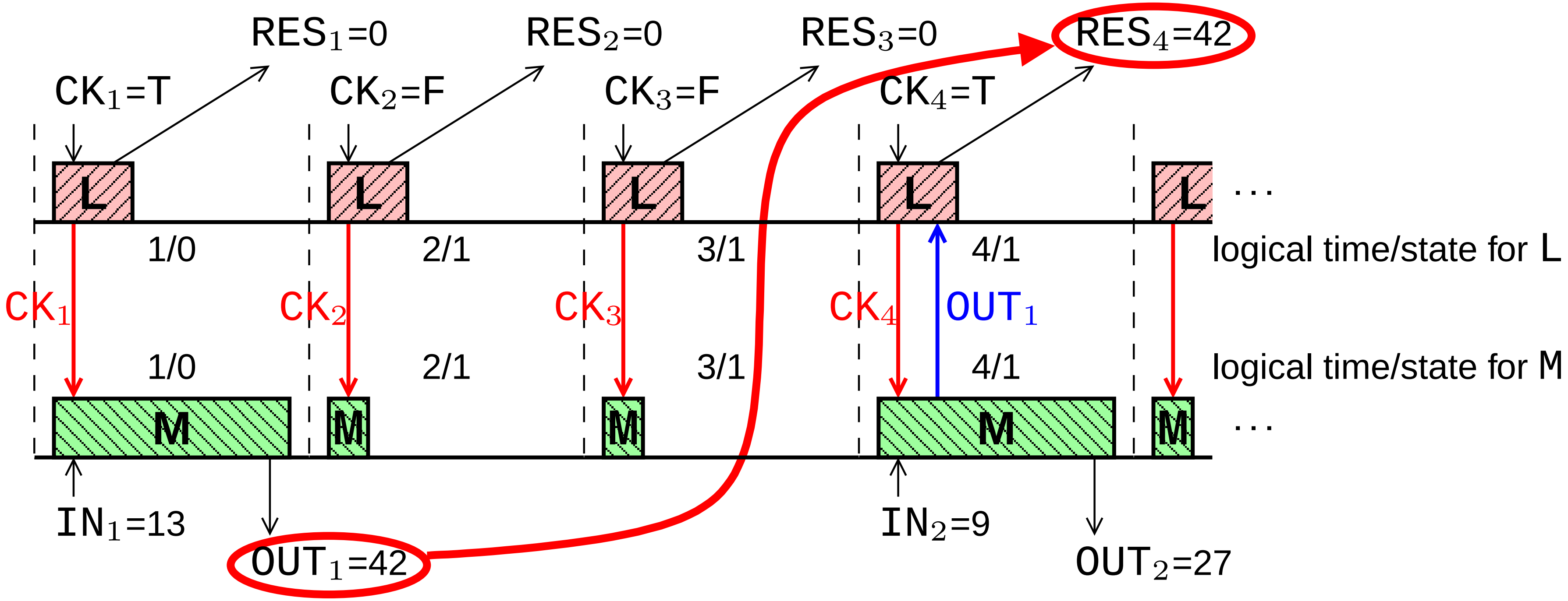
location `M` (rate `CK`)

```
state 0:
go(IN)
CK:=receive(L)
if (CK) then {
  OUT:=SLOW(IN)
  write(OUT)
  goto 1
} else {
  goto 0
} endif
```

```
state 1:
go(IN)
CK:=receive(L)
if (CK) then {
  send(L,OUT)
  OUT:=SLOW(IN)
  write(OUT)
} else {
} endif
goto 1
```

The `go(CK,IN)` has been split into {
`go(CK)` on location `L`
`go(IN)` on location `M`

A run of the distributed FILTER



The value of CK is sent by L to M at each cycle of the base rate

➪ location M runs at the speed of the base rate instead of CK

If the communications take 1, then the global WCET is still 8

How to improve this?

We want location `M` to run at the speed of `CK`

- ➪ This would give enough time for the computation of `SLOW`
- ➪ For this, location `L` must not send `CK` to location `M`
  - We can use an existing bisimulation for detecting and suppressing branchings like `if(CK)` on location `M`
  - For this bisimulation to work, the `go(IN)` action must be moved inside the `then` branch on location `M`

    Makes sense because `IN` is expected only when `CK` is `true`
- ➪ The two programs will be logically desynchronized

Moving the go downward

Only the locations whose rate is not the base rate

A simple forward traversal of the program:

Moving the go downward

Only the locations whose rate is not the base rate

A simple forward traversal of the program:

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loc. M (rate CK) - state 0
go(IN)
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   write(OUT)
   goto 1
else
   goto 0
endif
```

Moving the go downward

Only the locations whose rate is not the base rate

A simple forward traversal of the program:

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loc. M (rate CK) - state 0
go(IN)
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```

$\leadsto$

```
loc. M (rate CK) - state 0
if (CK) then
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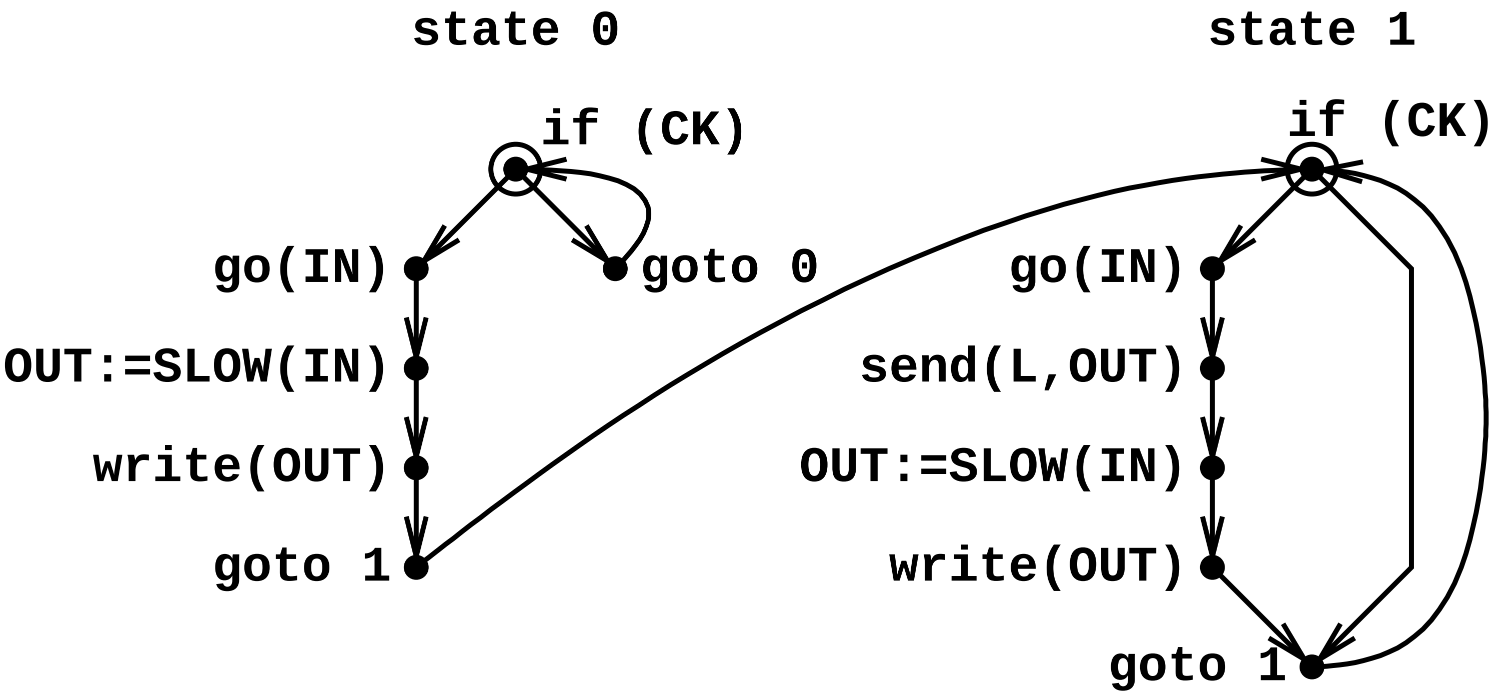
   write(OUT)
   goto 1
else
   goto 0
endif
```

Suppressing useless branchings

Bisimulation fully presented in [Caspi, Fernandez & Girault 1995]



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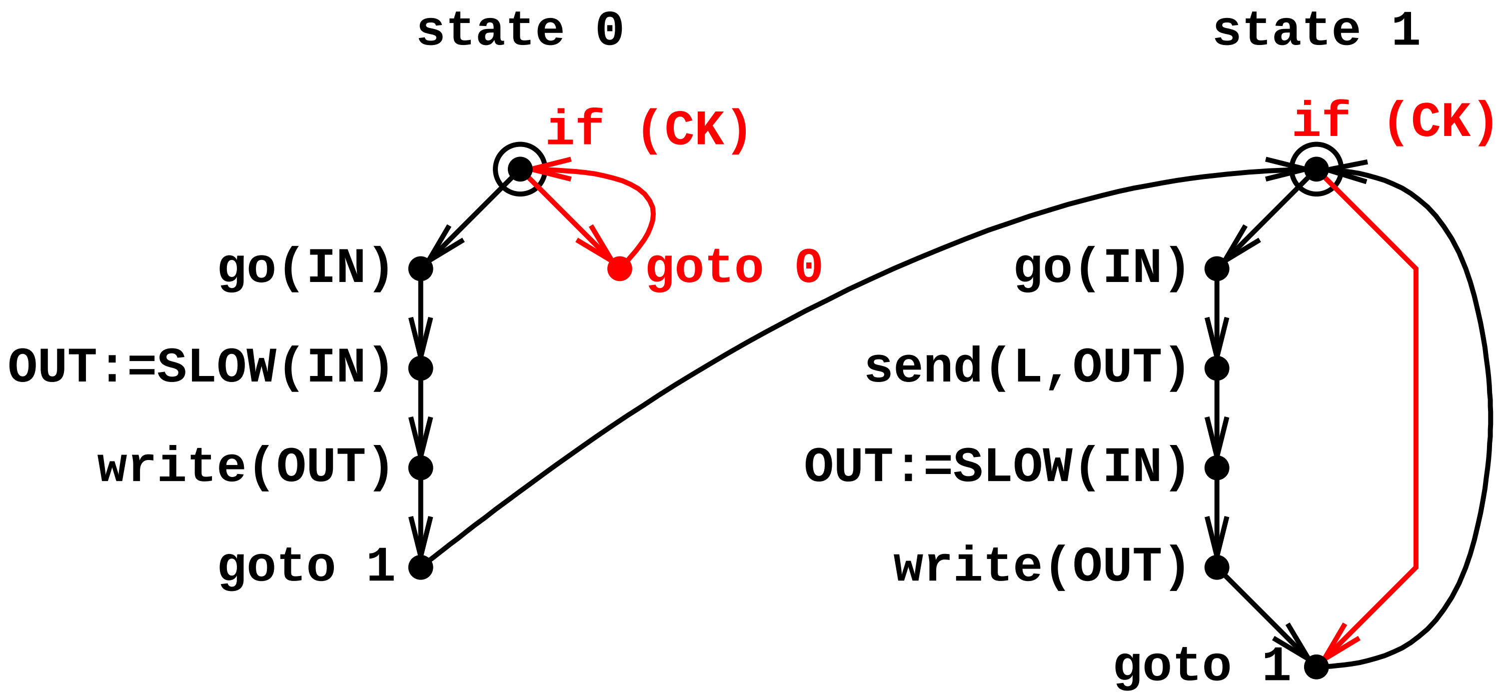

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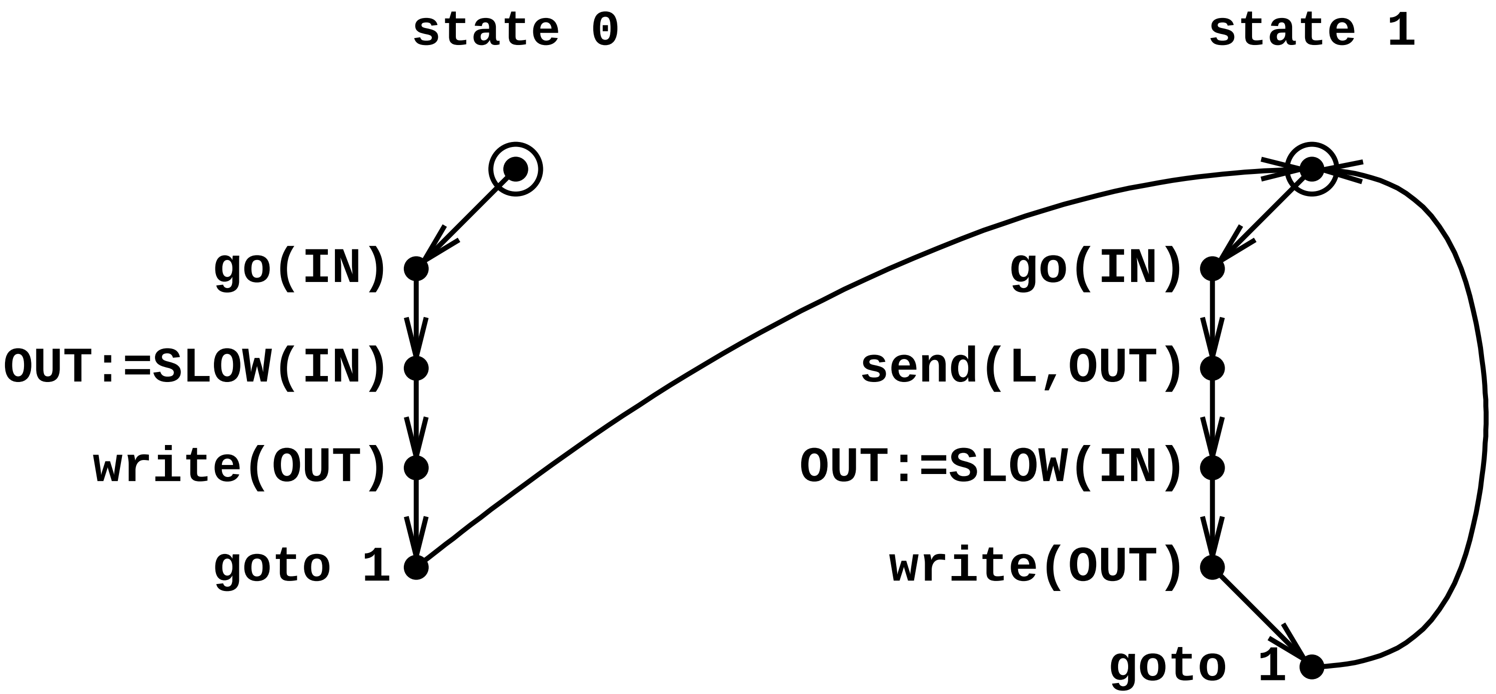

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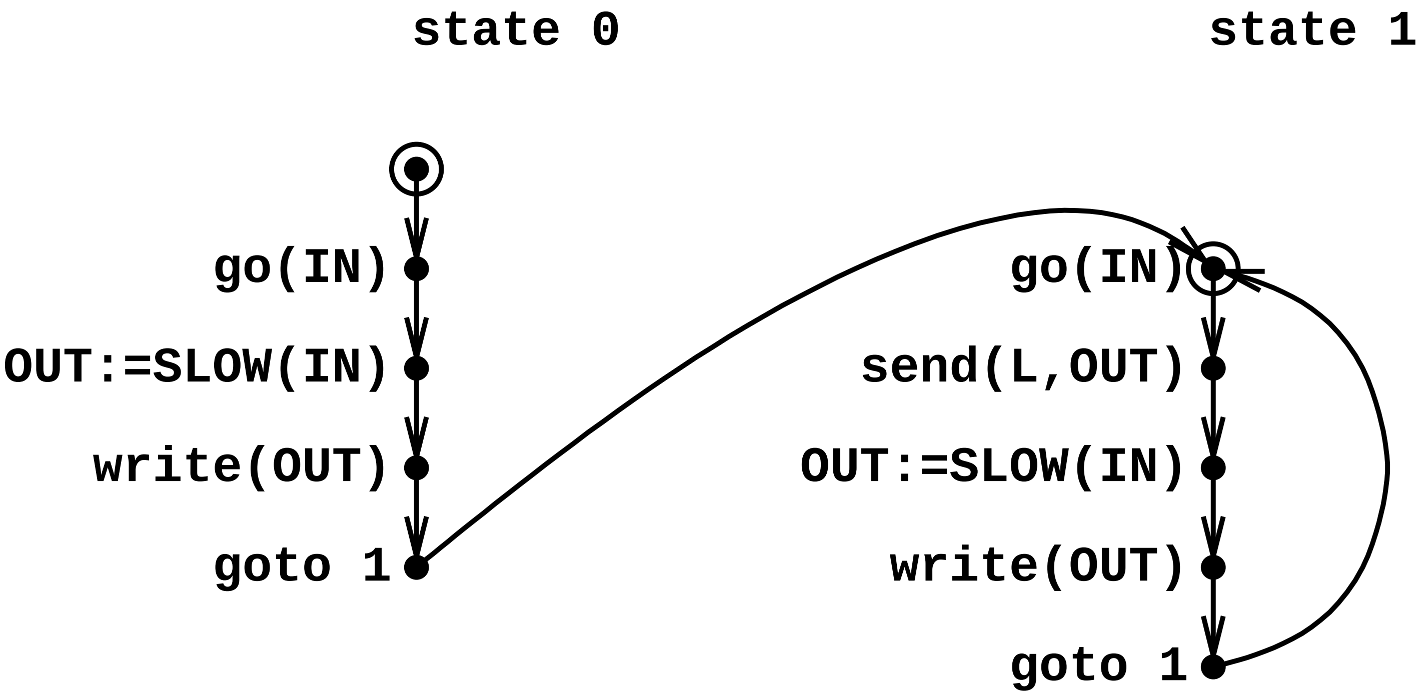


Final result

location `L` (rate base)

```
state 0:
go(CK)
if (CK) then {
  RES:=0
  write(RES)
  V:=0
  goto 1
} else {
  RES:=V
  write(RES)
  goto 0
} endif
```

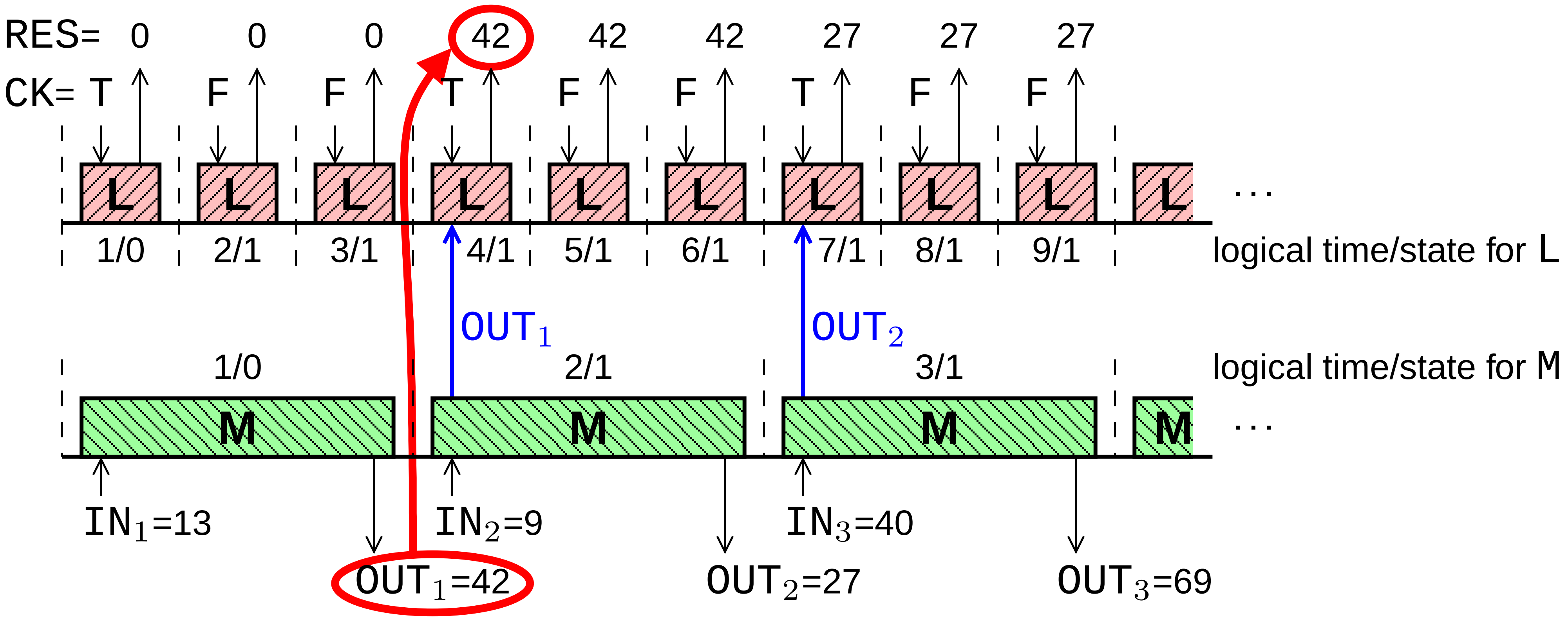
```
state 1:
go(CK)
if (CK) then {
  OUT:=receive(M)
  RES:=OUT
  V:=OUT
} else {
  RES:=V
} endif
write(RES)
goto 1
```

location `M` (rate `CK`)

```
state 0:
go(IN)
OUT:=SLOW(IN)
write(OUT)
goto 1
```

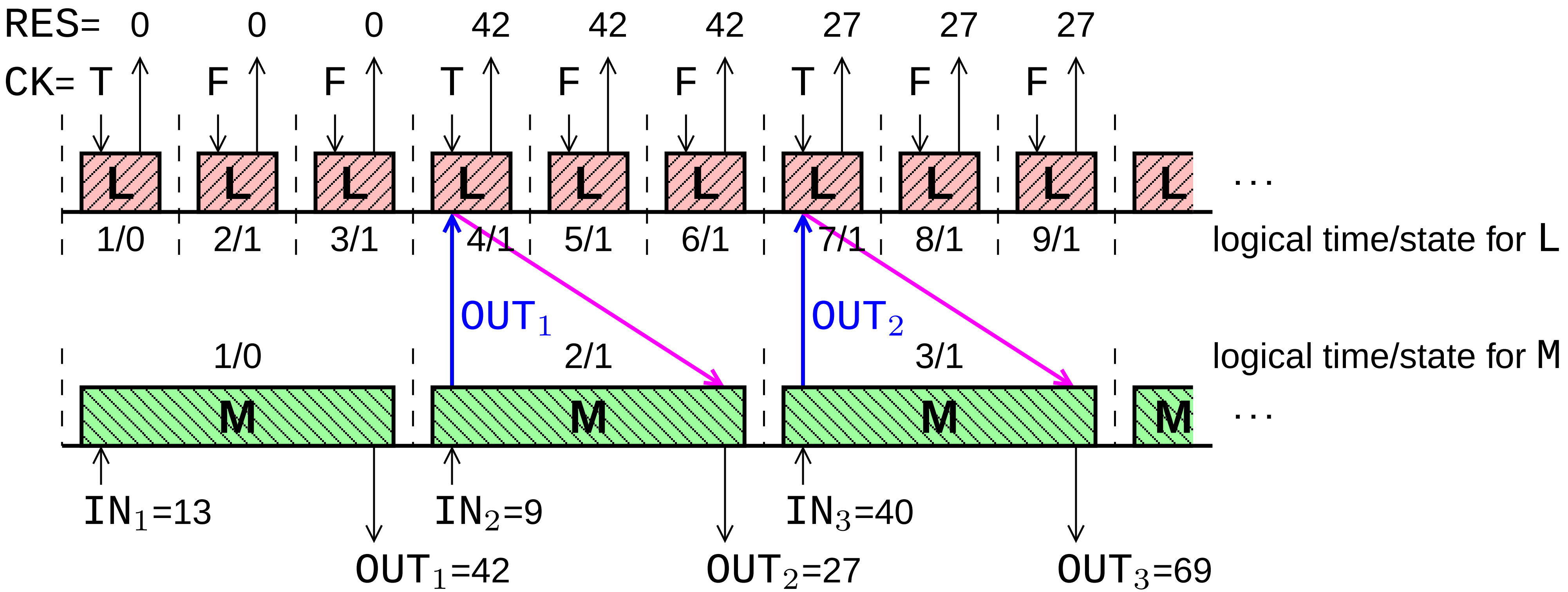
```
state 1:
go(IN)
send(L,OUT)
OUT:=SLOW(IN)
write(OUT)
goto 1
```

A run of the newly distributed FILTER



The period of L is one third of the period of M

A run of the newly distributed `FILTER`



Dummy communications can finally be added to guarantee bounded FIFO queues

Validating the synchronous abstraction

We have to compare the WCET with the execution loop period

But our program is distributed into n tasks. So:

- We compute the n WCET
- We compute the total utilisation factor
- We check the Liu & Layland conditions (mono-processor case)

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location	`L`	`M`
WCET	2	8
rate	5	15

Validating the synchronous abstraction

We have to compare the WCET with the execution loop period

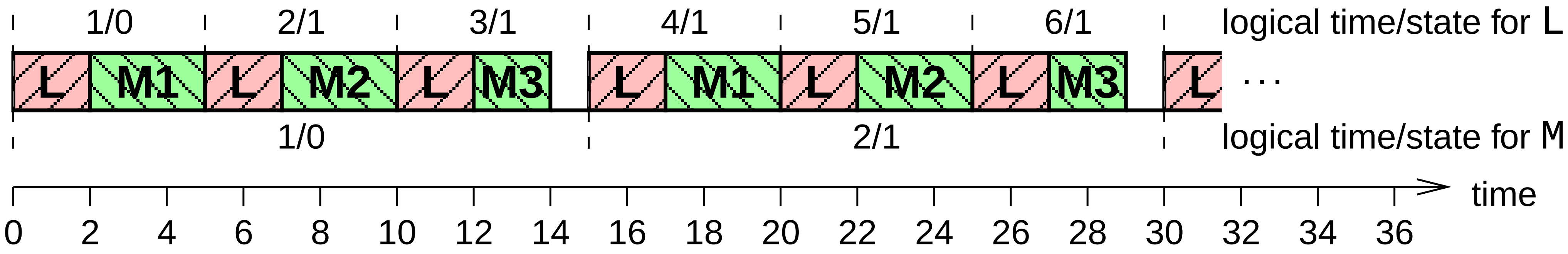
But our program is distributed into n tasks. So:

- We compute the n WCET
- We compute the total utilisation factor
- We check the Liu & Layland conditions (mono-processor case)

location	`L`	`M`
WCET	2	8
rate	5	15

$$\frac{\mathbf{2}}{\mathbf{5}} + \frac{\mathbf{8}}{\mathbf{15}} = \frac{\mathbf{14}}{\mathbf{15}} \leq \mathbf{1}$$

RTOS implementation



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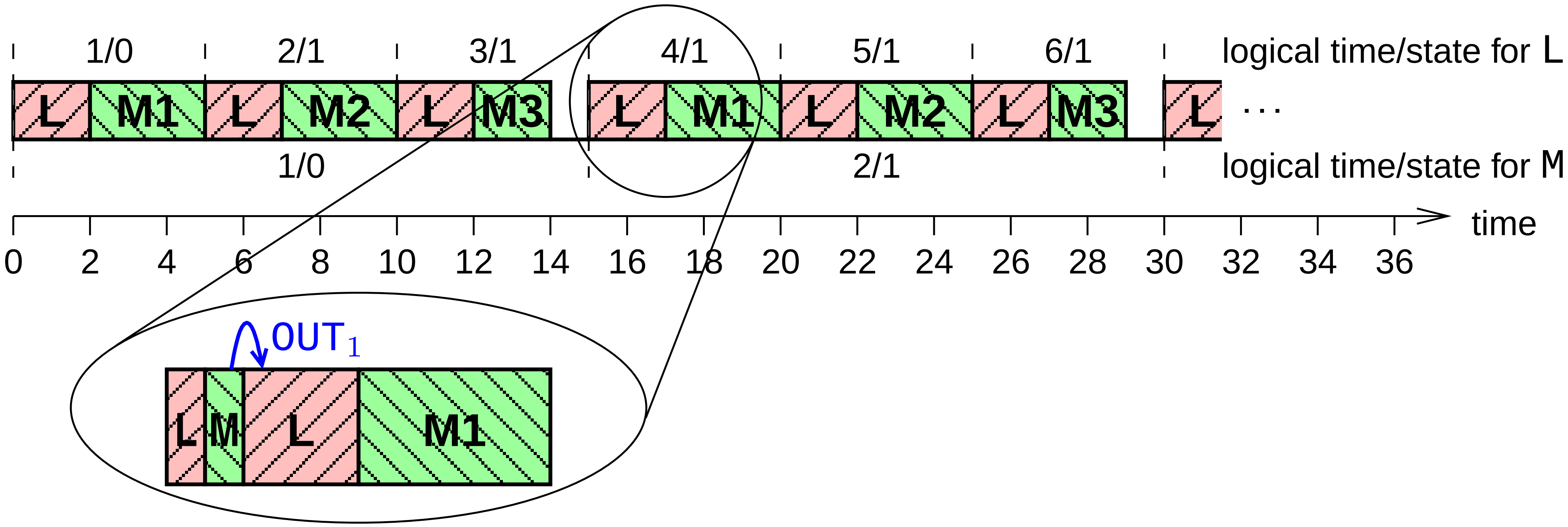
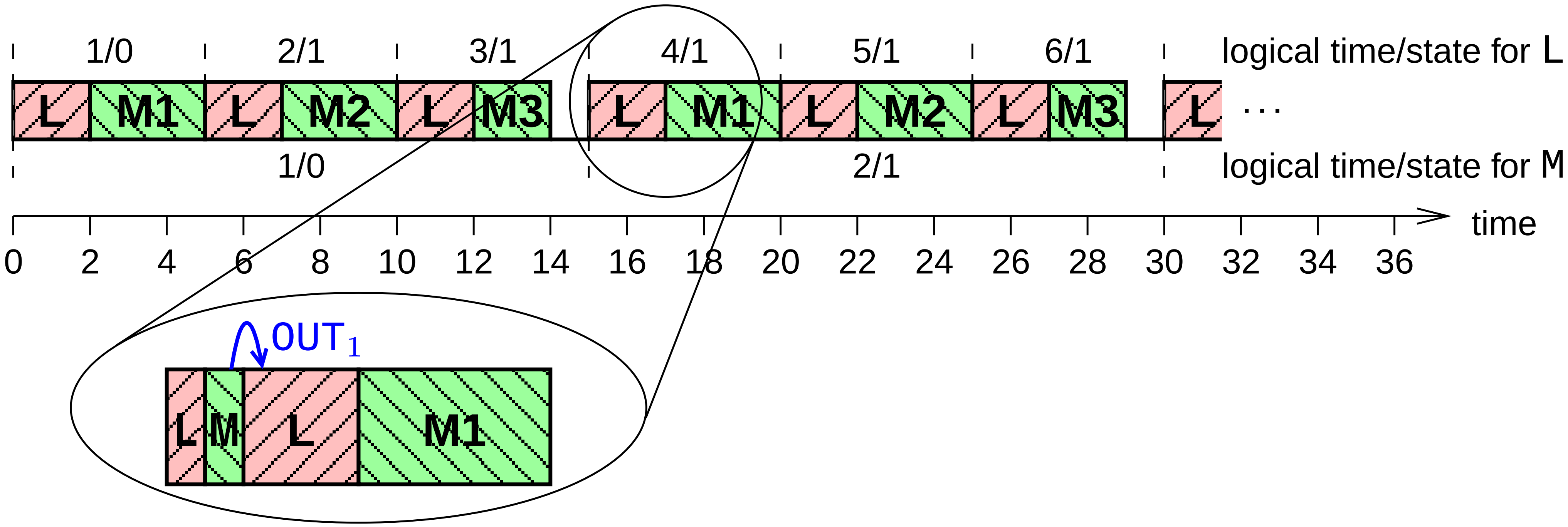
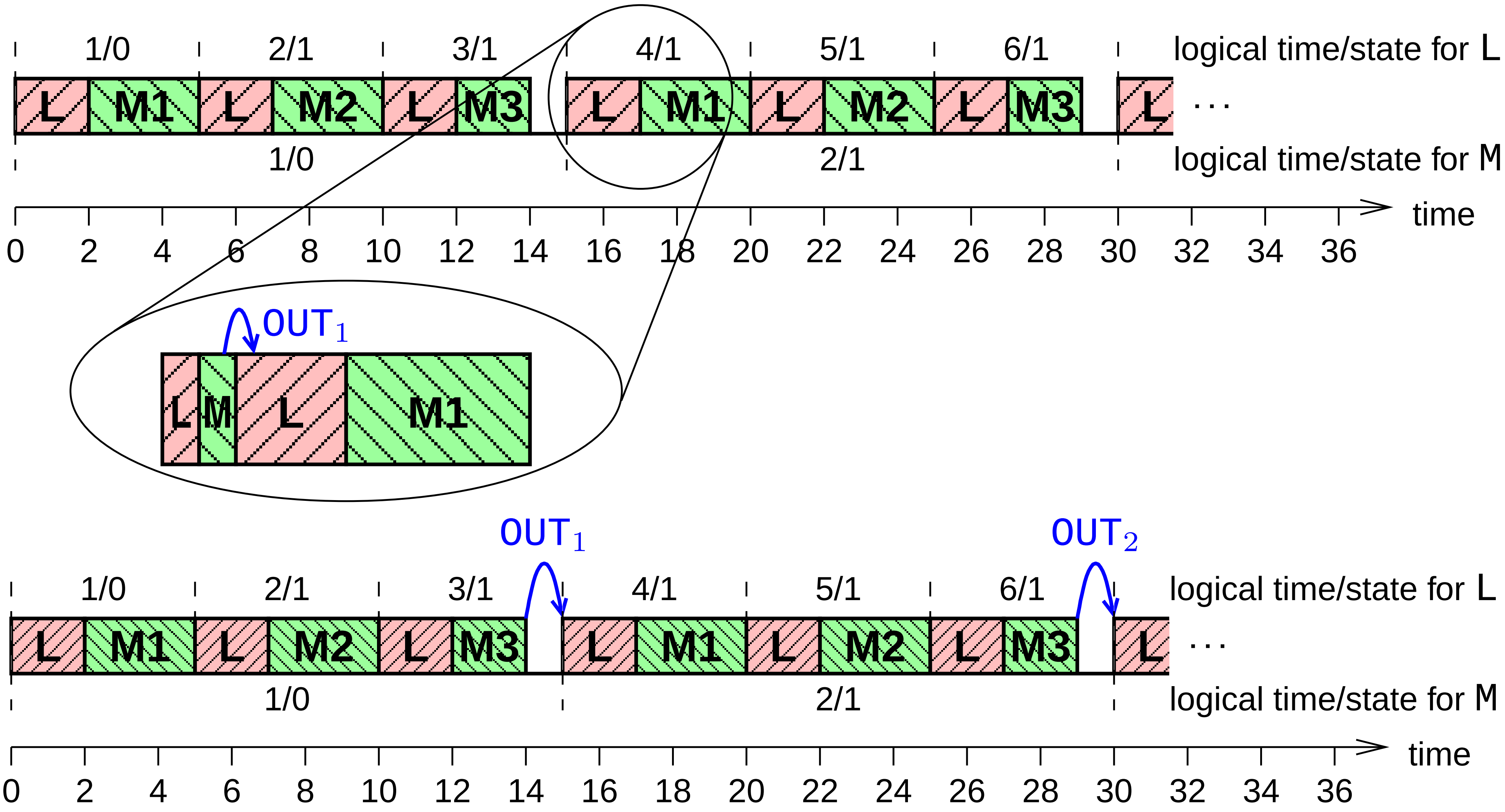


RTOS implementation



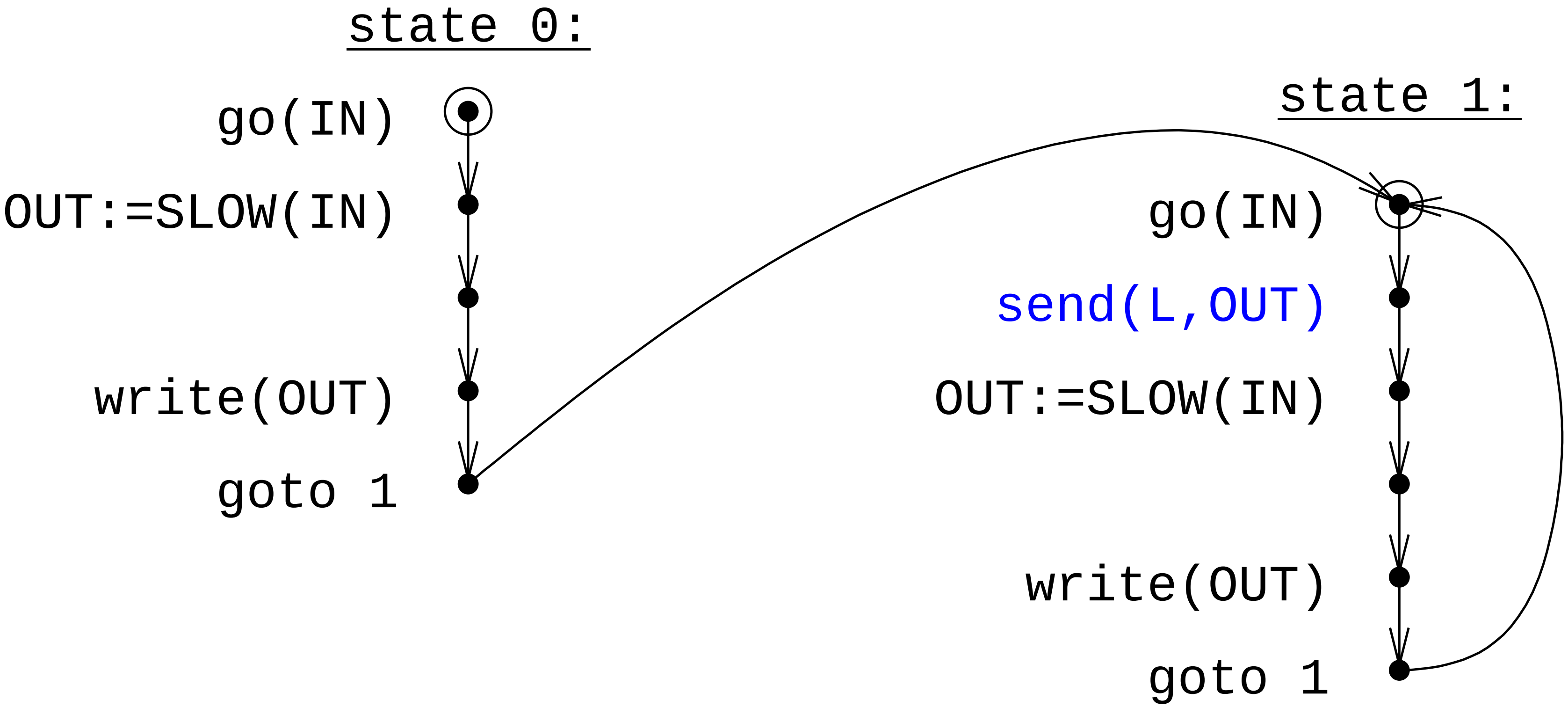
This mechanism relies on the preemption mechanism of the RTOS!

RTOS implementation



Data-flow analysis

Program of location M



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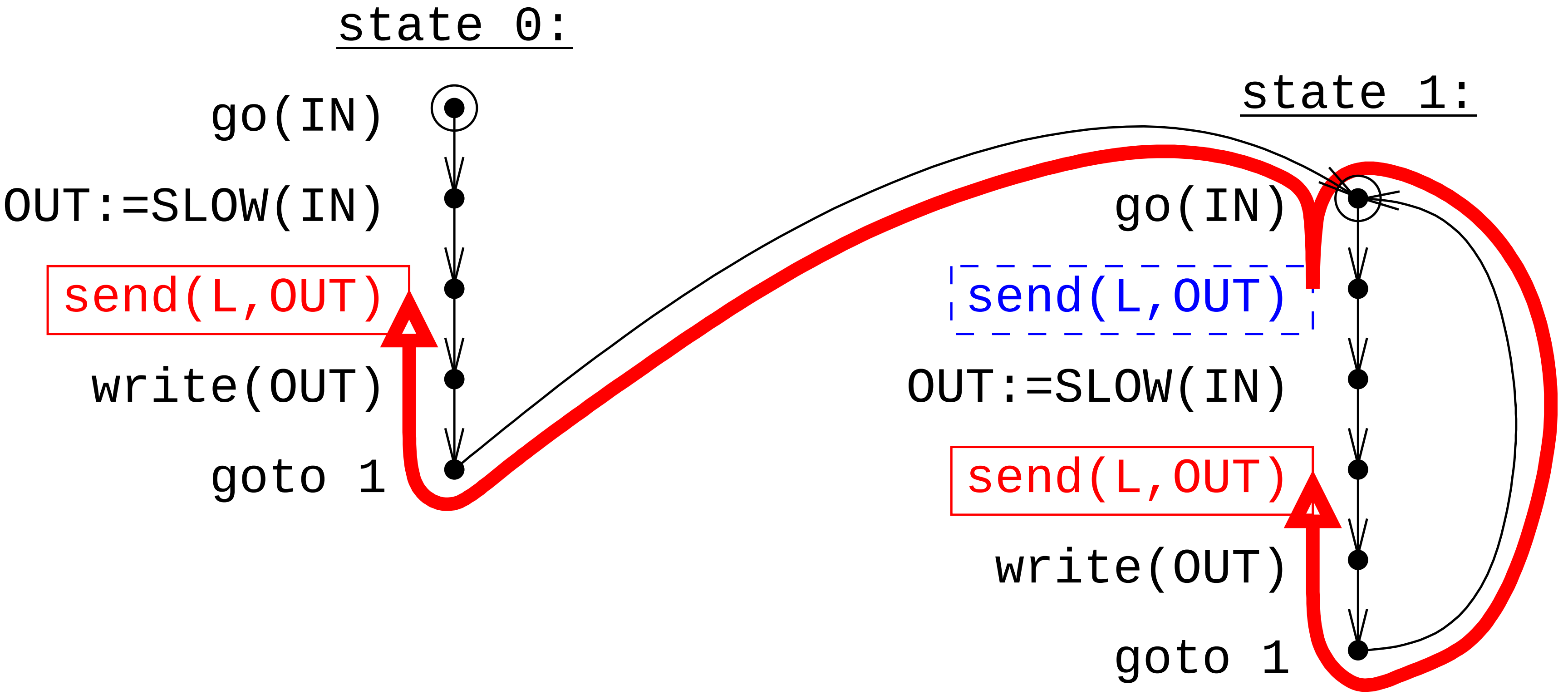

Data-flow analysis

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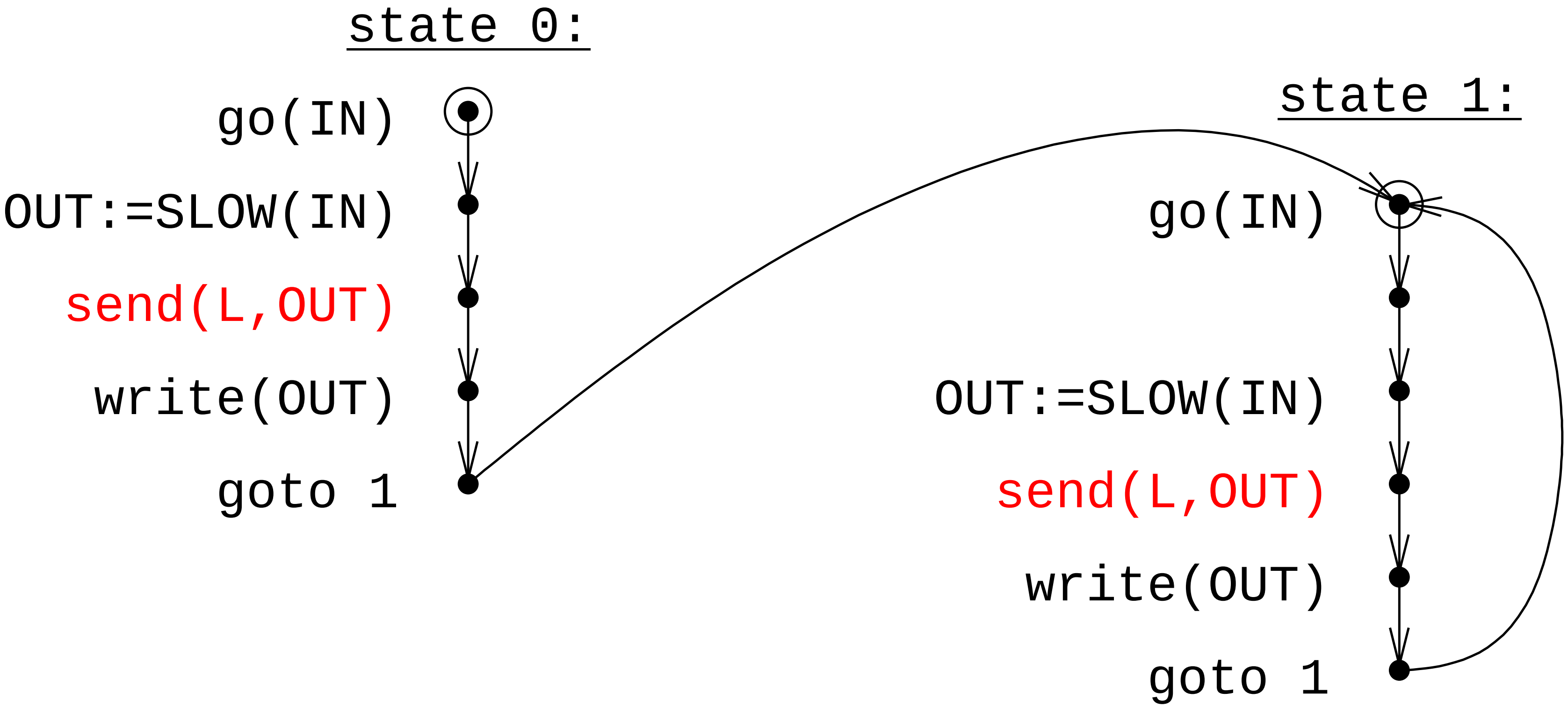

state 0:

```
go(IN)
OUT:=SLOW(IN)
send(L,OUT)
write(OUT)
goto 1
```

state 1:

```
go(IN)

OUT:=SLOW(IN)
send(L,OUT)
write(OUT)
goto 1
```

Two applications

1. Clock driven automatic distribution of Lustre programs
2. Automatic rate desynchronisation of Esterel programs

Lustre is synchronous, declarative, data-flow

All objects are flows: infinite sequences of typed data

Clocks

Each flow has a clock (= *first class abstract type*)

➪ The sequence of instants where the flow bears a value

Any Boolean flow defines a new clock: the sequence of instants where it bears the value `true`

Flows can then be upsampled (`current`)
and downsampled (`when`)

A program must be correctly clocked

One clock is called the base clock of the program:
➪ the sequence of its activation instants (the Esterel `tick`)

The set of clocks is a tree whose root is the base clock

Syntax

```
node FILTER (CK : bool; (IN : int) when CK)
    returns (RES : int; (OUT : int) when CK);
let
    RES = current ((0 when CK) -> pre OUT);
    OUT = SLOW (IN);
tel.
function SLOW (A : int) returns (B : int);
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The `SLOW` function is long duration task

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The clock tree is:

base {RES, CK}
↓
CK {IN, OUT}

An example of a run of FILTER

base clock cycle number	1	2	3	4	5	6	7	8	9	...
CK	T	F	F	T	F	F	T	F	F	...
IN	14			9			23			...

An example of a run of `FILTER`

base clock cycle number	1	2	3	4	5	6	7	8	9	...
`CK`	`T`	`F`	`F`	`T`	`F`	`F`	`T`	`F`	`F`	...
`IN`	14			9			23			...
`OUT = SLOW(IN)`	42			27			69			...

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`0 when CK`	0			0			0			...

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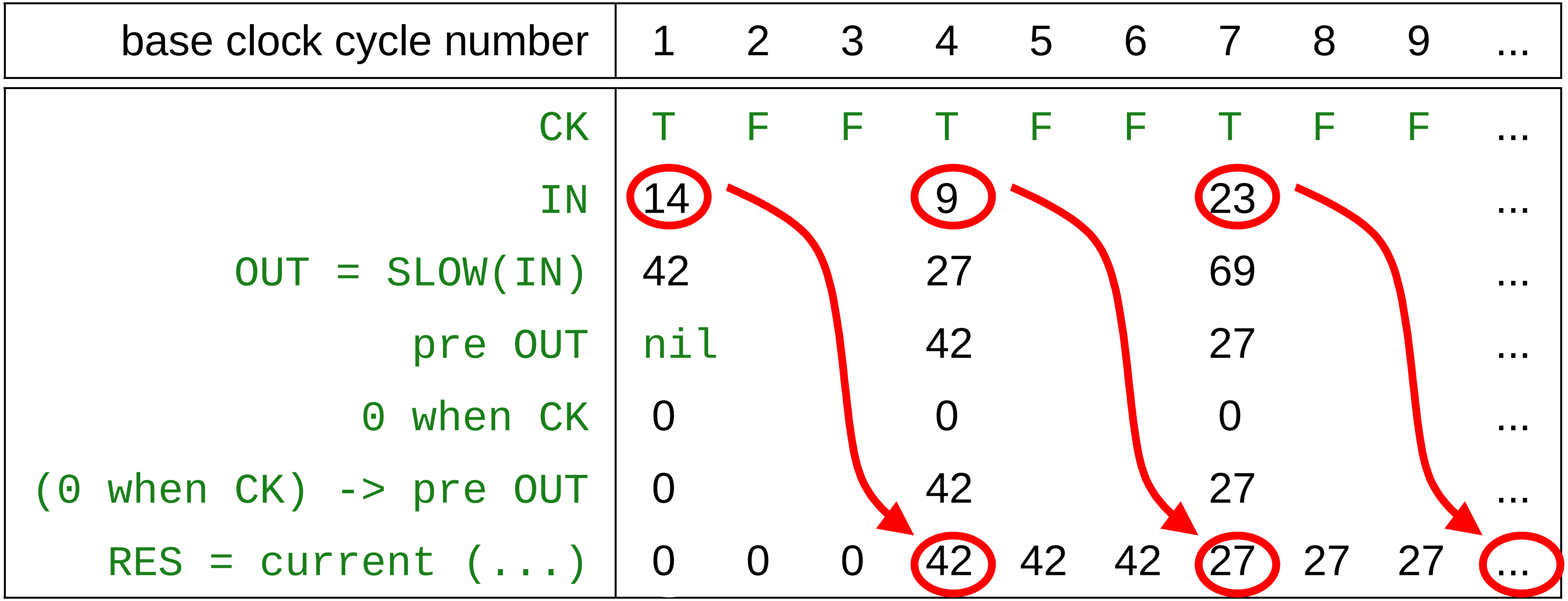
- `OUT` must be available at the same clock cycle of `CK` as `IN`

An example of a run of `FILTER`



base clock cycle number	1	2	3	4	5	6	7	8	9	...
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`(0 when CK) -> pre OUT`	0			42			27			...
`RES = current (...)`	0	0	0	42	42	42	27	27	27	...

- These are logical instants
- `OUT` must be available at the same clock cycle of `CK` as `IN`
- `RES` must be available at the next clock cycle of `CK`

Clock-driven automatic distribution

Automatic distribution:

From a centralised source program and some distribution specifications, we build automatically as many programs as required by the user

Their combined behaviour will be functionnaly equivalent to the behaviour of the initial centralised program

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Clock-driven:

The user specifies which clock goes to which computing location

➪ Partition of the set of clocks of the centralised source program

One subset for each desired computing location

Related work

- Giotto compiler: [Henzinger, Horowitz & Kirsch 2001]

- Asynchronous tasks in Esterel: [Paris 1992]

- Automatic distribution in Signal: [Maffeis 1993], [Aubry, Le Guernic, Machard 1996], [Benveniste, Caillaud & Le Guernic 2000]

- Distributed implementation of Lustre over TTA: [Caspi, Curic, Maignan, Sofronis, Tripakis & Niebert 2003]

Conclusion and future research

This new distribution method:

- is implemented in the `ocrep` tool:

`http://www.inrialpes.fr/pop-art/people/girault/Ocrep`

- works equally well with Lustre and Esterel programs
- allows the writing and compiling of synchronous programs with long duration tasks

Some future plans:

- To adapt this method to Decade programs in order to obtain code mobility

  Decade is a dynamic higher-order synchronous data-flow programming language [Colaço et al 2004]