GRL: a Formal Language for the Specification of GALS Systems

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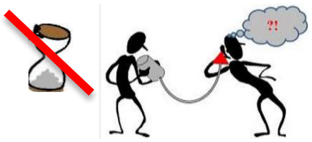
  - Several synchronous systems, different speeds
  - Arbitrary delays in communications
  - Nondeterministic behaviour

1s, 2s, 3s, …,

rendezvous



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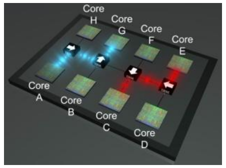

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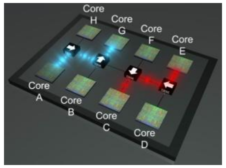

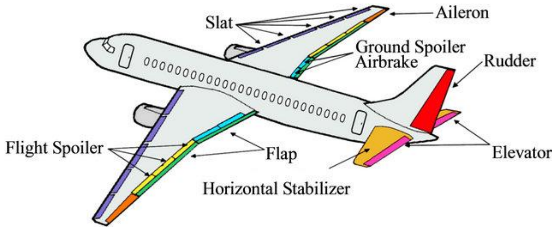

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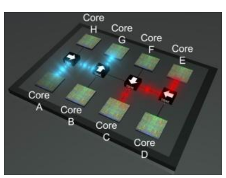
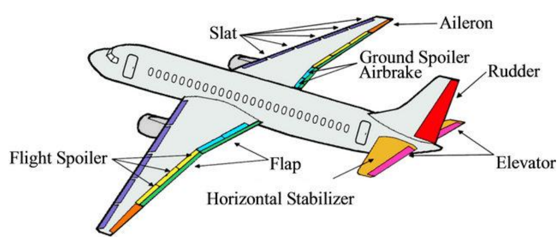
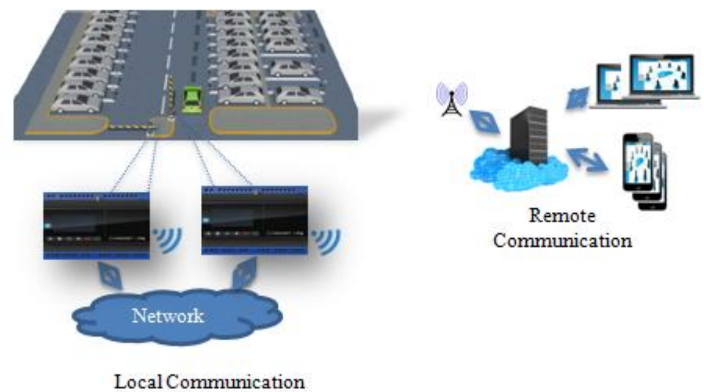






Formal Verification of GALS Systems

- **Problem:**
  - Hard to design and debug
  - Safety-critical applications
- **Formal modeling and verification:**
  - Powerful automatic tools
  - Correctness of the design process
- **However:**
  - Expertise in formal methods required
  - Scalability to industrial-size applications
- **Solution:**

GRL (GALS Representation Language)

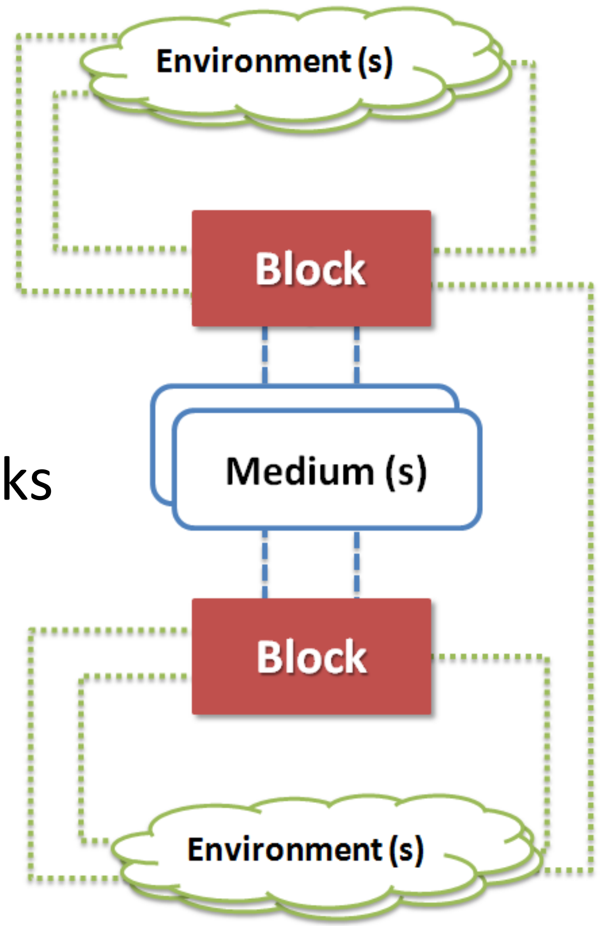
Rationale for GRL (GALS Representation Language)

- User convenience
  - Unified language (synchronous and asynchronous)
  - Modular modeling
  - Abstraction
  - Easy-to-use
- Efficient formal verification
  - Formal semantics
  - Pivot language (industrial tools, CADP [1] toolbox)

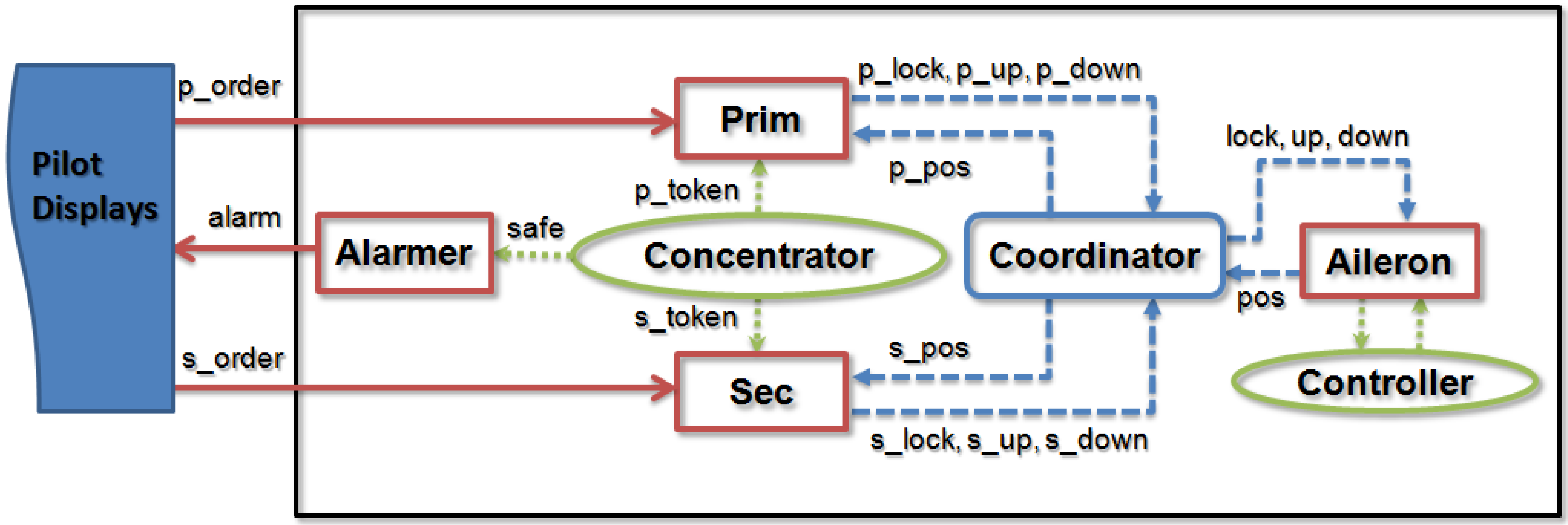
[1] Construction and Analysis of Distributed Processes
http://cadp.inria.fr/

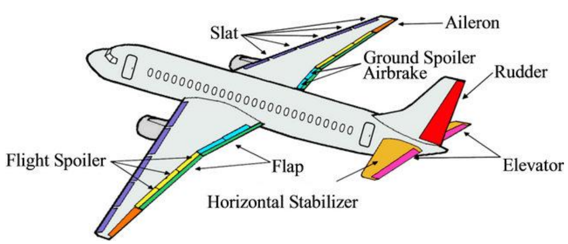
GRL in a nutshell

- Synchronous systems
  - **Blocks:** synchronous behaviour
  - Based on the dataflow model
- Asynchronous composition
  - **Mediums:** communication between blocks
  - **Environments:** external constraints
  - Inspired by process algebraic languages
- Imperative flavour



Running Example



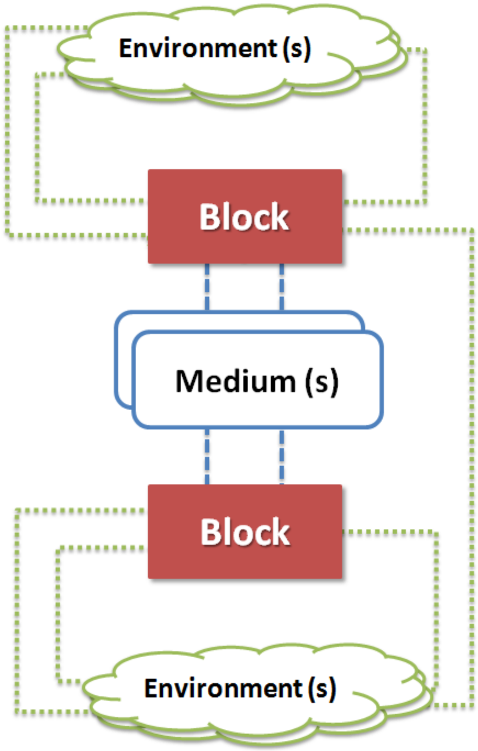


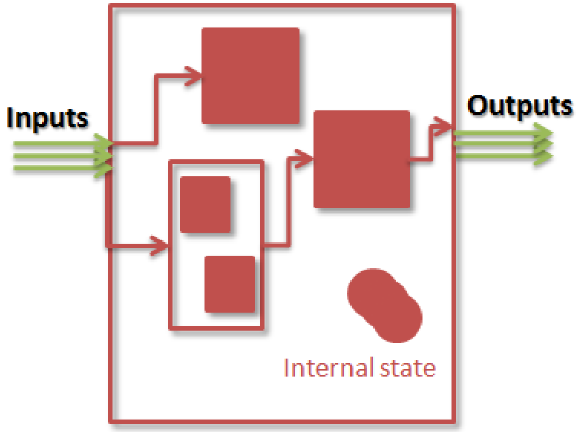
Flight Control System (FCS)
Airbus

block
medium
environment

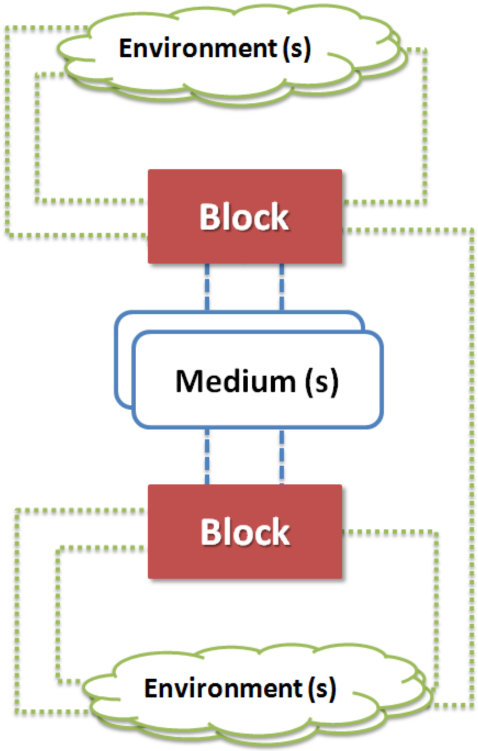
Blocks

- Cyclic behaviour (active):
  - Discrete deterministic steps
    1. Consume inputs
    2. Compute a reaction
    3. Produce outputs
  - Memory maintained: **permanent** variables
  - Atomic
- Composition of subblocks





Blocks



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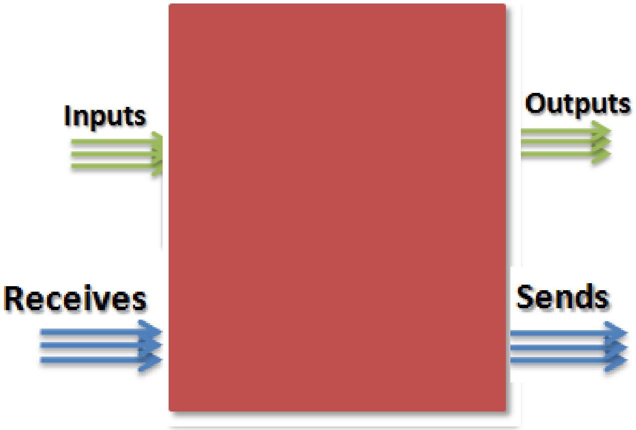
- Receive, Send: asynchronous communication



Blocks: Simple Example

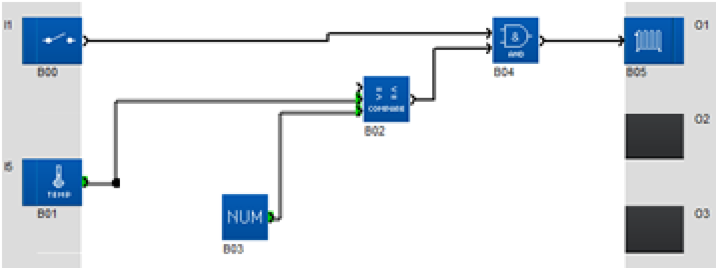
```
block Heater (in Switch : bool; in Sensor : nat; out Is_On : bool) is

  allocate Comparator [Strictly_Inferior] as B02,
           NUM [3] as B03,
           AND as B04,

  temp c1 : bool, c2 : nat

  B03 (?c2);
  B02 (_; Sensor, c2; ?c1);
  B04 (Switch; c1; ?Is_On)

end block
```



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Physical interactions

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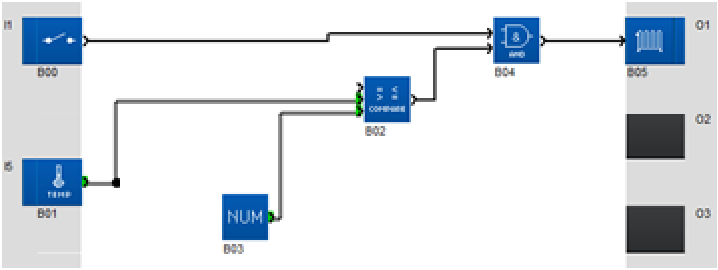

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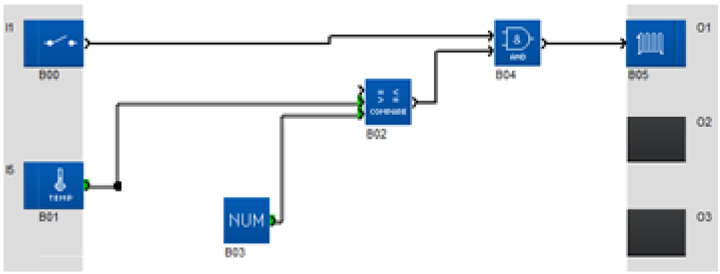
end block
```

Creation of instances
Separate memories



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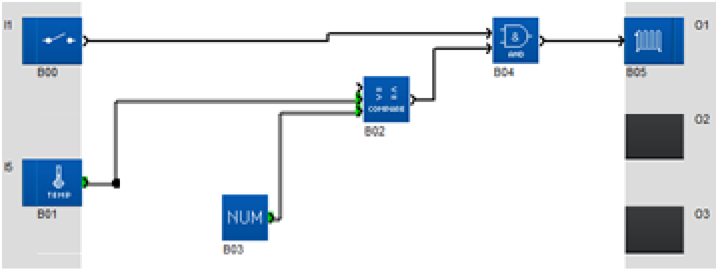
end block
```

Temporary variables



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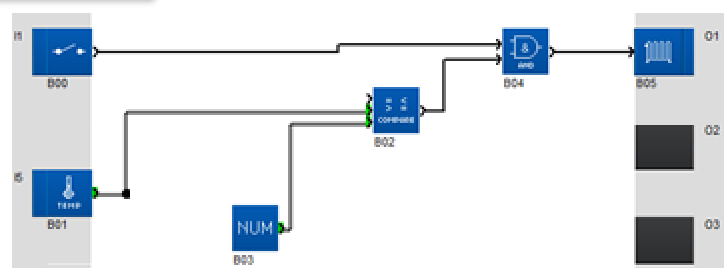
end block
```

Synchronous composition



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end block
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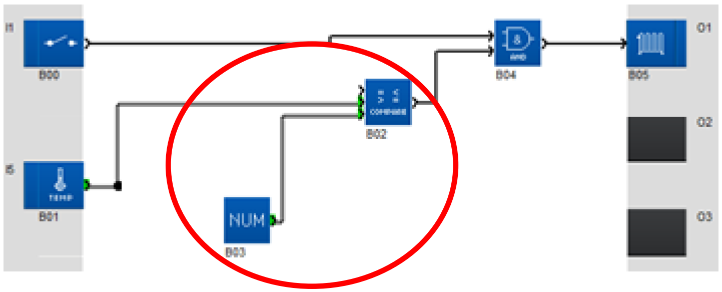
Data communication



Blocks: FCS Example

Physical interactions

```
block  Ail (in spo : bool; out cpo : nat)
           {receive lock, up, down :bool; send  apo : nat} is
    perm pos : nat := 0
    if (not (lock) and spo) then
        if up then pos := pos + 1
        elsif down then pos := pos + 1
        end if
    end if;
    cpo := pos;
    apo := pos
end block
```

Blocks: FCS Example

Interactions inside a network

```
block  Ail  (in spo : bool; out cpo : nat)
            {receive lock, up, down :bool; send  apo : nat} is
    perm pos : nat := 0
    if (not (lock) and spo) then
        if up then pos := pos + 1
        elsif down then pos := pos + 1
        end if
    end if;
    cpo := pos;
    apo := pos
end block
```

Blocks: FCS Example

Memory
initialization

```
block  Ail  (in spo : bool; out cpo : nat)
            {receive lock, up, down :bool; send  apo : nat} is
  perm pos : nat := 0
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    end if;
    cpo := pos;
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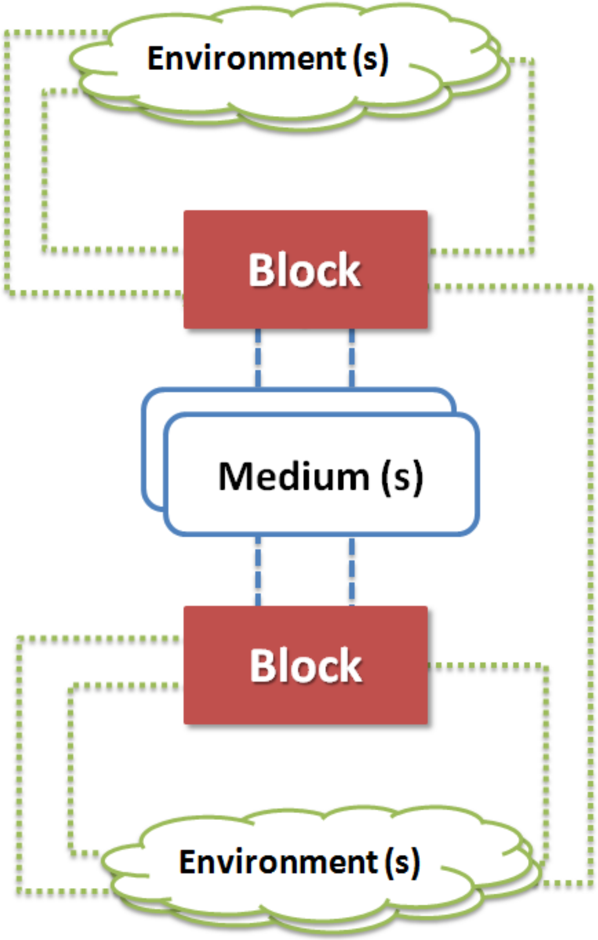
end block
```

Memory update

Mediums

- Modeling of asynchronous communication
- Activated on demand (passive)
  - Several connected blocks, different instants
  - Nondeterminism
- *Signal* statements to control activation



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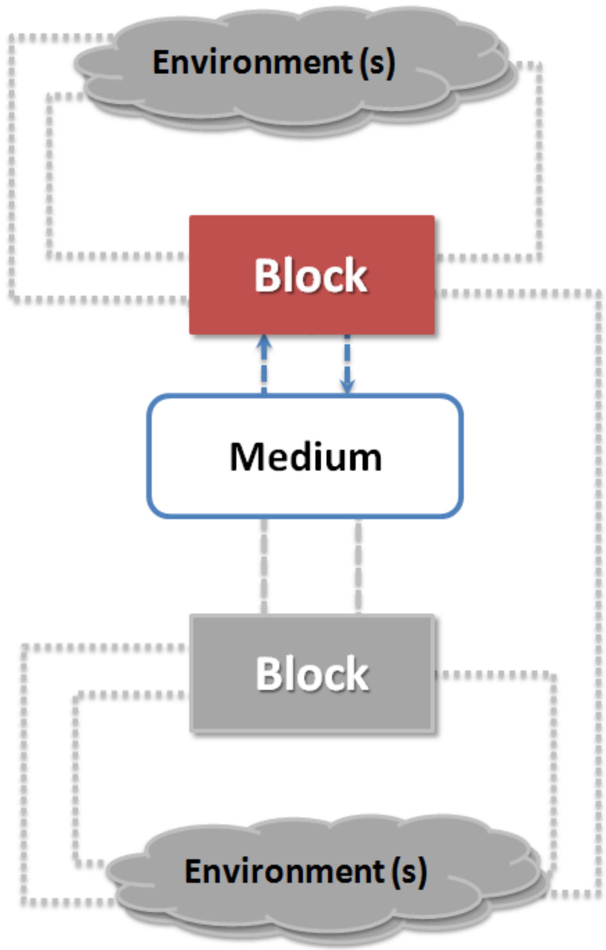

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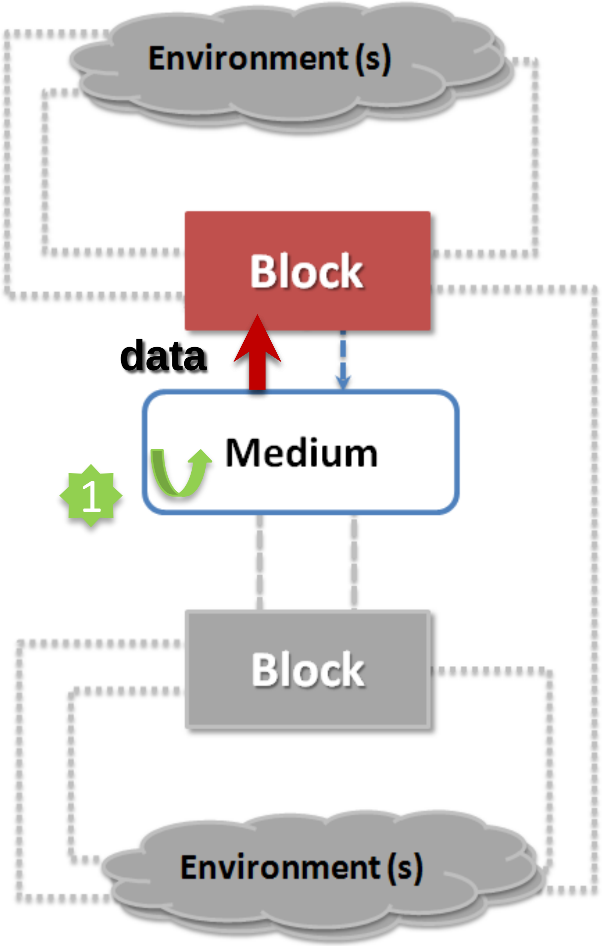

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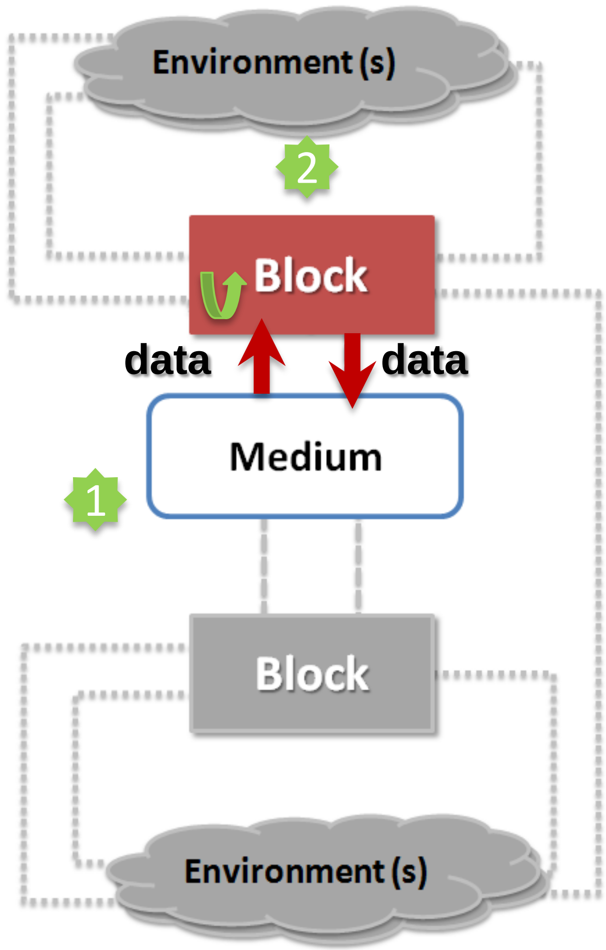

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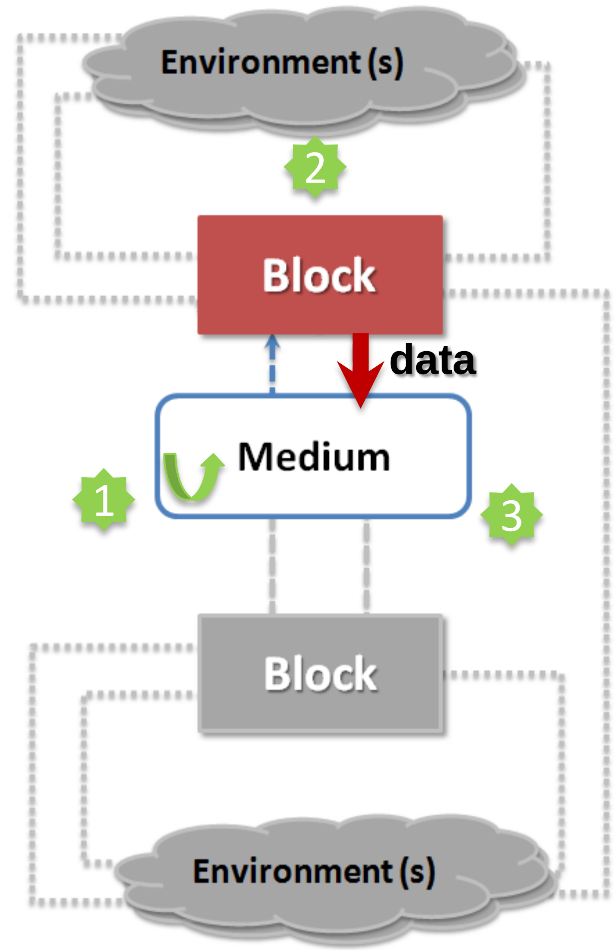

Mediums: FCS Example

```
medium Coord {receive apo : nat | send lock; up; down : bool |
              receive lp, up, dp : bool | send app : nat |
              receive ls, us, ds : bool | send aps : nat} is

  perm lock_bu : bool := true, up_bu, down_bu : bool := false, apo_bu : nat := 0
  select
    on lp, up, dp  -> lock_bu := lp; up_bu := up; down_bu := dp
    []   on ls, us, ds  -> lock_bu := ls; up_bu := us; down_bu := ds
    []   on apo -> apo_bu := apo
    []   on ?app -> app := apo_bu
    []   on ?aps -> aps := apo_bu
    []   on ?lock,?up, ?down  ->  lock := lock_bu ; up := up_bu ; down := down_bu
  end select

end medium
```

Buffers for transited data

Mediums: FCS Example

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     []   on apo -> apo_bu := apo
     []   on ?app -> app := apo_bu
     []   on ?aps -> aps := apo_bu
     []   on ?lock,?up, ?down  ->  lock := lock_bu ; up := up_bu ; down := down_bu
   end select

end medium
```

Nondeterministic choice

Mediums: FCS Example

Data reception

```
medium Coord {receive apo : nat | send
              receive lp, up, dp : bool | s   d app : nat |
              receive ls, us, ds : bool | send aps : nat} is

    perm lock_bu : bool := true, up_bu, down_bu : bool := false, apo_bu : nat := 0
    select
      on lp, up, dp  -> lock_bu := lp; up_bu := up; down_bu := dp
      []   on ls, us, ds  -> lock_bu := ls; up_bu := us; down_bu := ds
      []   on apo -> apo_bu := apo
      []   on ?app -> app := apo_bu
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      []   on ?lock,?up, ?down  ->  lock := lock_bu ; up := up_bu ; down := down_bu
    end select

end medium
```

Mediums: FCS Example

Data reception

Signal statement

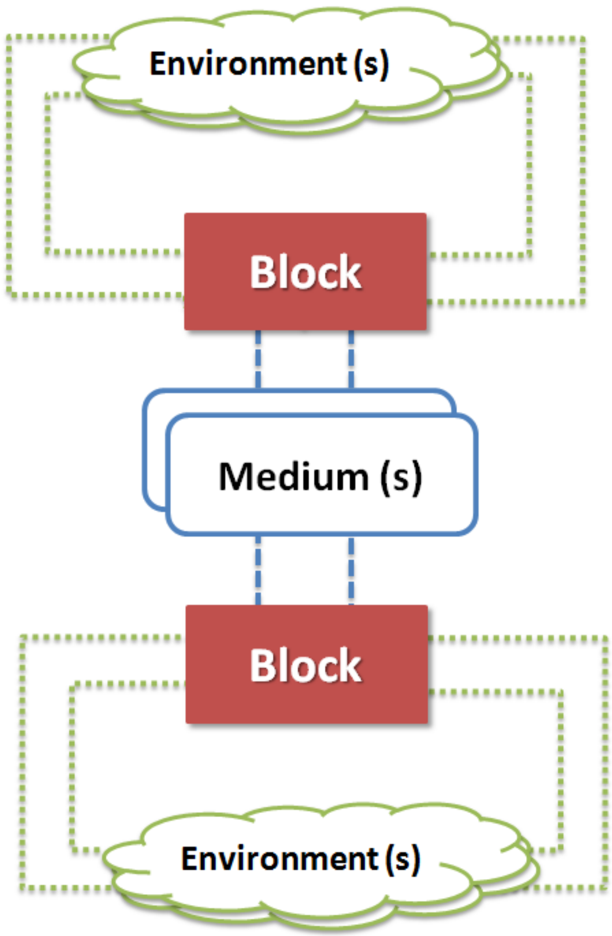
```
medium Coord {receive apo : nat | send                                  |
              receive lp, up, dp : bool |        app : nat |
              receive ls, us, ds : bool | send aps : nat} is

   perm lock_bu : bool := true, up_bu, down_                  _bu : nat := 0
   select
     on lp, up, dp  -> lock_bu := lp; up_bu := up; down_bu := dp
   []   on ls, us, ds  -> lock_bu := ls; up_bu := us; down_bu := ds
   []   on apo -> apo_bu := apo
   []   on ?app -> app := apo_bu
   []   on ?aps -> aps := apo_bu
   []   on ?lock,?up, ?down  ->  lock := lock_bu ; up := up_bu ; down := down_bu
   end select

end medium
```

Environments

- Modeling of constraints
  - Logical constraints between blocks
  - Physical constraints
- Activated on demand (passive)
- *Signal* statements to control activation



Environments: FCS Example

```
environment Conc (out p_tok:bool | out                :bool) is
   perm p_alive, s_alive:bool := true
   if p_alive then
     select
       on ?p_tok -> p_tok := true   -- primary responds
       [] p_alive := false   -- primary fails
     end select
   elsif s_alive then
     select
       on ?s_tok -> s_tok := true   -- secondary responds
       [] s_alive := false  -- secondary fails
     end select
   else
       on ?alarm -> alarm := true
   end if
end  environment
```

Safety state of Prim and Sec

Environments: FCS Example

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environment Conc (out p_tok:bool | out          :bool) is
  perm p_alive, s_alive:bool := true
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Safety state of Prim and Sec

Prim has the priority of control

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Safety state of Prim and Sec

Prim has the priority of control

Priority gave to Sec

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    else
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    end if
end  environment
```

Safety state of Prim and Sec

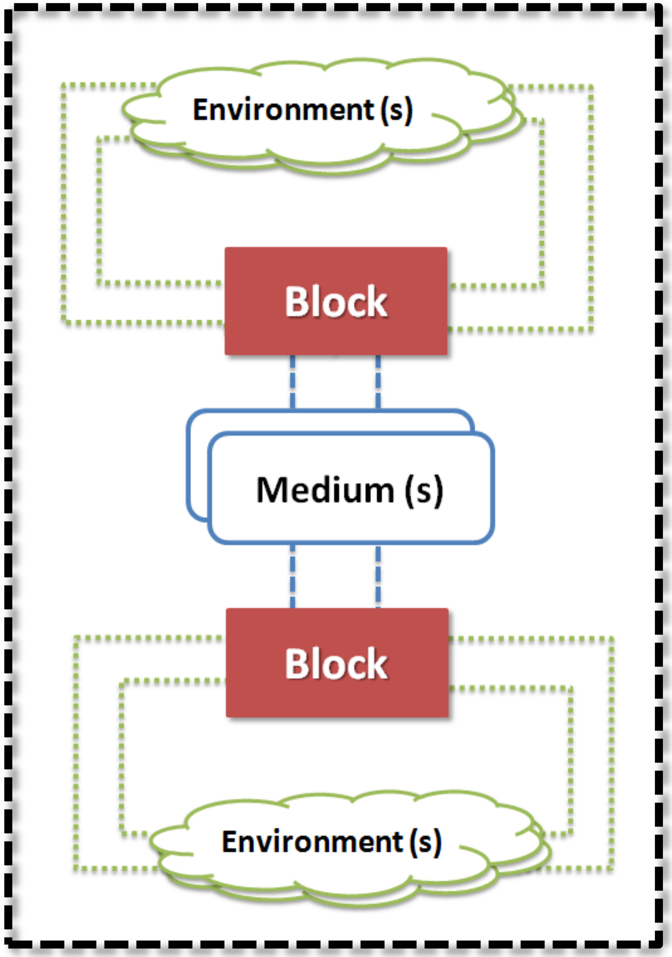
Prim has the priority of control

Priority gave to Sec

Aileron out of control

Systems

- Composition of blocks, mediums, and environments
- No direct connection between blocks
- Communication between blocks and mediums (resp., environments) by message-passing rendezvous



Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
   allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
            Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
   temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
        s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
        c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
   network
      Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
      Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
      Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
      Alarmer (safe; ?alarm)
   constrainedby
      Conc (?p_tok | ?s_tok | ?safe),
      Ctrl (c_pos | ?ok)
   connectedby
      Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Creation of instances

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
             Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
         s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
         c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
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        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Block invocations

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
             Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
         s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
         c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Block invocations

Environment invocations

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
             Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
         s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
         c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Block invocations

Environment invocations

Medium invocations

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
             Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
         s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
         c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
            Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
          s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
          c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Data communication

Systems: FCS Example

system FlightControlSystem (p_ord**,** s_ord **: nat,** alarm **: bool) is**

allocate FBWComp **as** Prim**,** FBWCom **as** Sec **,** Ail **as** Ail**,** Alarmer **as** Alarmer**,**

Conc **as** Conc**,** Ctrl **[**10**] as** Ctrl**,** Coord **as** Coord

temp p_tok **: bool,** p_pos**: nat,** p_lck**,** p_up**,** p_dwn **: bool,**

s_tok **: bool, s**_pos**: nat,** s_lck**,** s_up**,** s_dwn **: bool,**

c_pos**,** pos **: nat,** lck, up, dwn **: bool,** safe, ok**: bool**

network

Prim **(**p_tok**;** p_ord**) {**p_pos**; ?**p_lck**, ?**p_up**, ?**p_dwn**},**

Sec **(**s_tok**;** s_ord**) {**s_pos**; ?**s_lck**, ?**s_up**, ?**s_dwn**},**

Ail **(**ok**; ?**c_pos**) {**lck**,** up**,** dwn**; ?**pos**},**

Alarmer **(**safe**; ?**alarm**)**

constrainedby

Conc **(?**p_tok **| ?**s_tok **| ?**safe**),**

Ctrl **(**c_pos **| ?**ok**)**

connectedby

Coord **{**pos **| ?**lck**, ?**up**, ?**dwn **|** p_lck**,** p_up**,** p_dwn **| ?**p_pos **|** s_lck**,** s_up**,** s_dwn **| ?**s_pos**}**

end system

Data communication

Systems: FCS Example

Visible from the outside world

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
              Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
          s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
          c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Systems: FCS Example

```
system FlightControlSystem (p_ord, s_ord : nat, alarm : bool) is
    allocate FBWComp as Prim, FBWCom  as Sec , Ail as Ail, Alarmer as Alarmer,
            Conc as Conc, Ctrl [10] as Ctrl, Coord as Coord
    temp p_tok : bool, p_pos: nat, p_lck, p_up, p_dwn : bool,
         s_tok : bool, s_pos: nat, s_lck, s_up, s_dwn : bool,
         c_pos, pos : nat, lck, up, dwn : bool, safe, ok: bool
    network
        Prim (p_tok; p_ord) {p_pos; ?p_lck, ?p_up, ?p_dwn},
        Sec (s_tok; s_ord) {s_pos; ?s_lck, ?s_up, ?s_dwn},
        Ail (ok; ?c_pos) {lck, up, dwn; ?pos},
        Alarmer (safe; ?alarm)
    constrainedby
        Conc (?p_tok | ?s_tok | ?safe),
        Ctrl (c_pos | ?ok)
    connectedby
        Coord {pos | ?lck, ?up, ?dwn | p_lck, p_up, p_dwn | ?p_pos | s_lck, s_up, s_dwn | ?s_pos}
end system
```

Visible from the outside world

Invisible from the ouside world

Formal Semantics of GRL

- Labelled transition systems
  - States: union of the memories of blocks, mediums, and environments
  - Initial state: initial values of memories
  - Labels: execution of blocks

    + visible inputs/outputs + visible receives/sends
  - Transition function: atomic execution of blocks with connected mediums and environments
- 145 rules of static semantics [2]
- 24 rules of structural operational semantics [2]

[2] available in a technical report of 130 pages

Tools for GRL

- GRL2LNT(20,000 lines):
  - Parser (2,000 lines): lexical and syntactic analysis
  - Automated translator to LNT, input language of CADP
  - Accurate and concise LNT
  - Improve scalability of model checking
- Enabled access to CADP
  - More than 40 tools
  - Explicit state exploration
  - Model-checking, equivalence checking, visual checking

Results for the FCS Example

- State space generation
  – 2,653 states
  – 7,406 transitions

- Reduction with branching bisimulation
  – 5 states
  – 1,287 transitions

- Formal verification with CADP enabled

Conclusion: GRL

- Versatile and modular description of
  - Synchronous systems
  - Asynchronous communication
  - Environment constraints
- Expressive and general-purpose
- Close to graphical data flow used in industry
- Easier to learn than full-fledged process algebra
- Efficient verification with CADP

Conclusion: ongoing work

- GRL and GRL2LNT applied on an industrial project
  - Crouzet Automation (Schneider Electric)
  - Networks of Programmable Logic Controllers

  ➔ **Positive feedback**
- Development of off-the-shelf blocks, mediums, and environments
- Automated GRL generation from industrial tools

  ➔ Automated verification chain
- Connection to synchronous verification tools (future work)

Thank You