Modeling Heterogeneous Real-time Components in BIP

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VERIMAG

Composition of Embedded Systems

Scientific and Industrial Issues

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Component-based construction – Objectives

Develop a rigorous and general basis for real-time system design and implementation:

- Concept of component and associated composition operators for incremental description and correctness by construction

- Concept for real-time architecture encompassing heterogeneity, paradigms and styles of computation e.g.
  - Synchronous vs. asynchronous execution
  - Event driven vs. data driven computation
  - Distributed vs. centralized execution

- Automated support for component integration and generation of glue code meeting given requirements

Approches involving components

- Theory such as process algebras and automata
- SW Component frameworks, such as
  - Coordination languages extensions of programming languages : Linda, Javaspaces, TSpaces, Concurrent Fortran, NesC
  - Middleware e.g. Corba, Javabeans, .NET
  - Software development environments: PCTE, SWbus, Softbench, Eclipse
- System modeling languages: SystemC, Statecharts, UML, Simulink/Stateflow, Metropolis, Ptolemy
- Architecture Description Languages focusing on non-functional aspects e.g. AADL

Lack of

- *frameworks treating interactions and system architecture as first class entities that can be composed and analyzed (usually, interaction by method call)*
- *rigorous models for behavior and in particular aspects related to time and resources.*

Sources of heterogeneity [Henzinger&Sifakis FM06]

Heterogeneity of interaction

- Atomic or non atomic
- Rendezvous or Broadcast
- Binary or n-ary

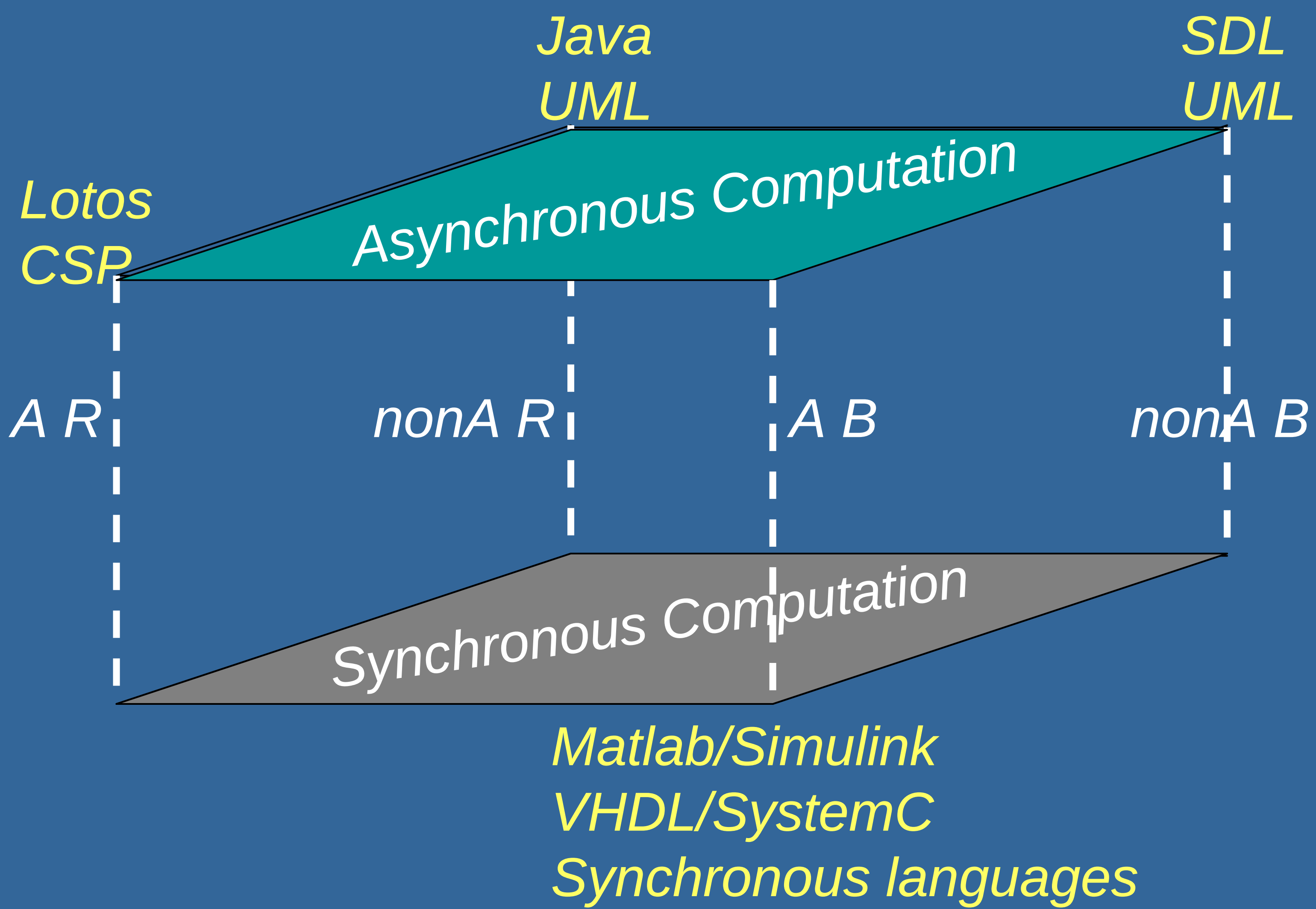
Heterogeneity of execution

- Synchronous execution
- Asynchronous execution
- Combinations of them

Heterogeneity of abstraction e.g. granularity of execution

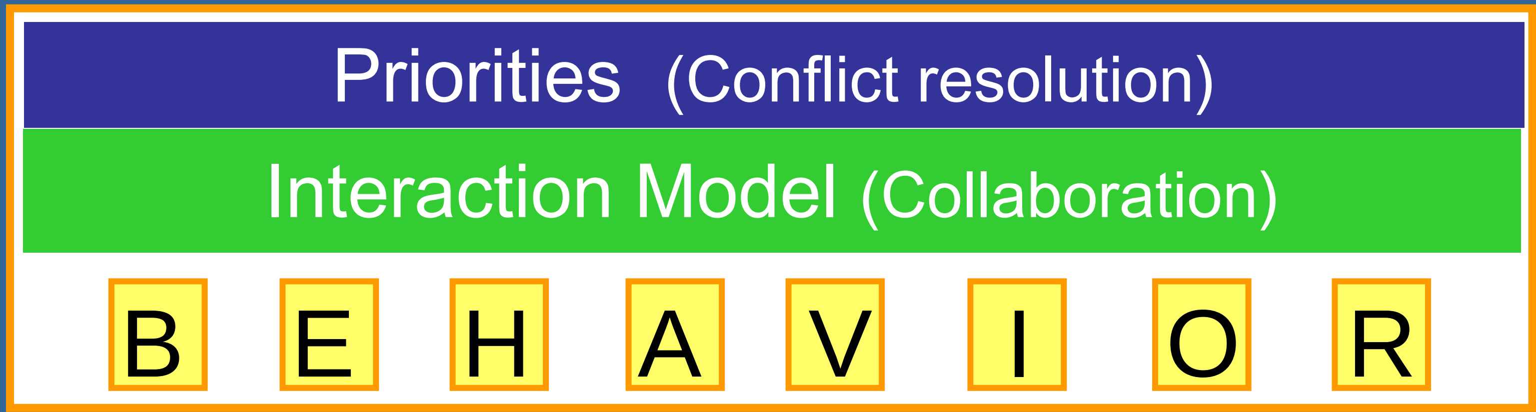
Sources of heterogeneity - Example

A: Atomic interaction   *R: Rendezvous*   *B: Broadcast*

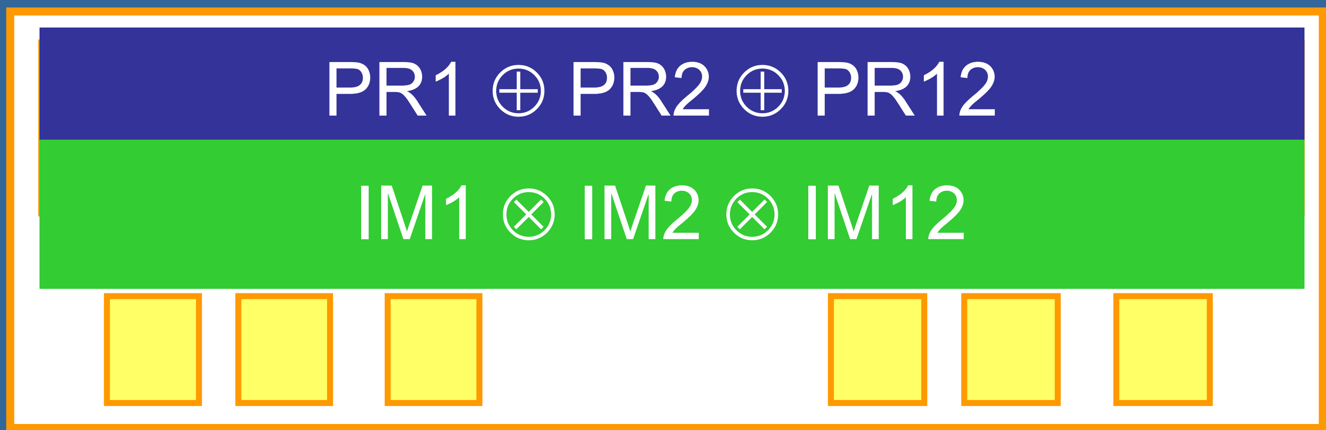


Component-based construction – The BIP framework

Layered component model



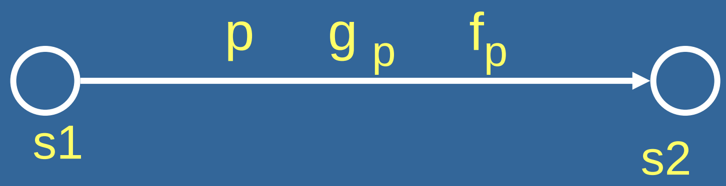
Composition (incremental description)

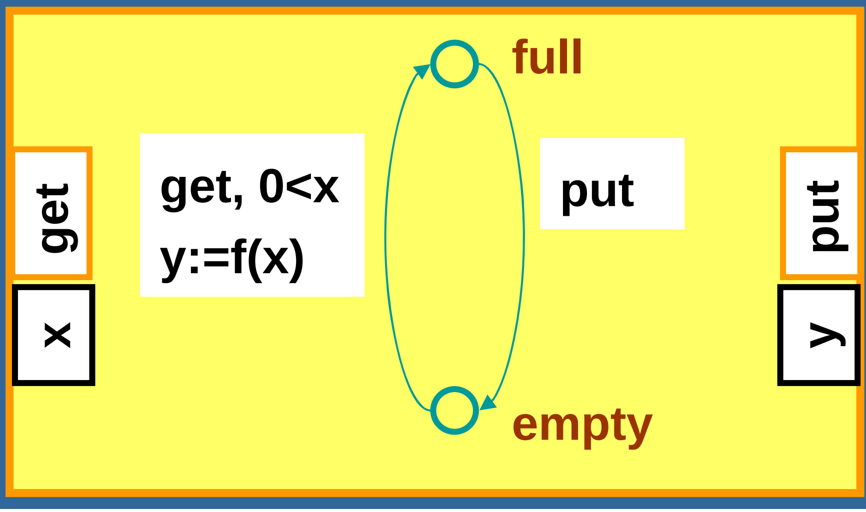


Component-based construction – The BIP framework: Behavior

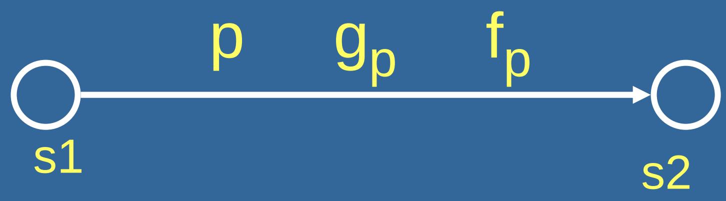
An atomic component has

- A set of ports P, for interaction with other components
- A set of control states S
- A set of variables V
- A set of transitions of the form
  - p is a port
  - g_p is a guard, boolean expression on V
  - f_p is a function on V (block of code)





Component-based construction – The BIP framework: Behavior



p: a port through which interaction is sought

g_p: a pre-condition for interaction through p

f_p : a computation (local state transformation)

Semantics

- **Enabledness:** g_p is true and some interaction involving p is possible
- **Execution:** interaction involving p followed by the execution of f_p

Overview

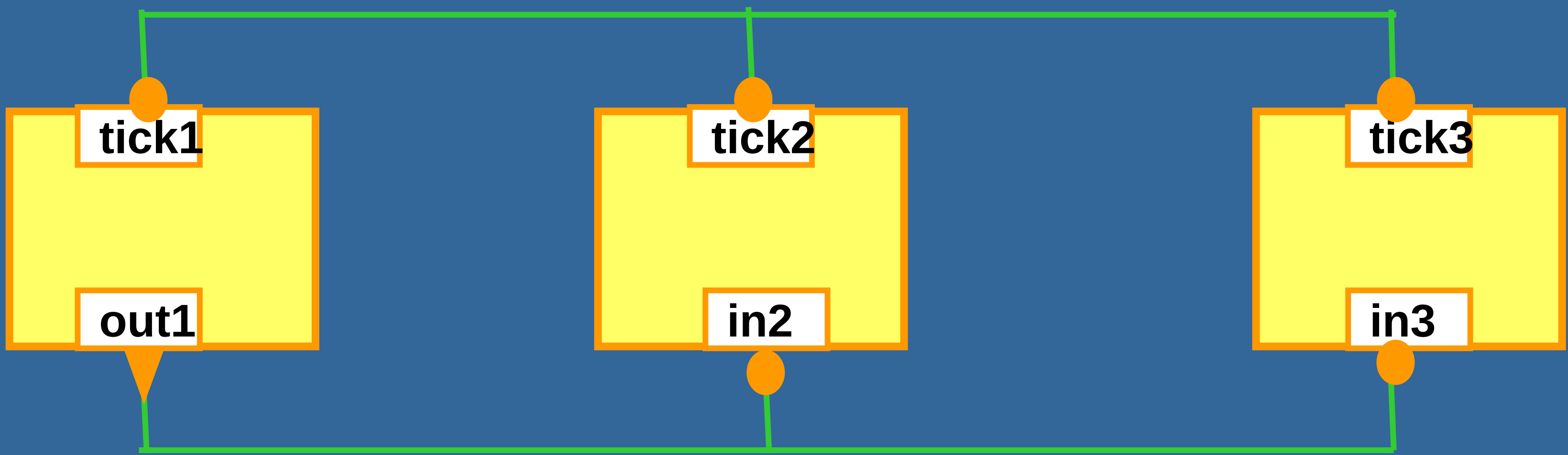
- Interaction modeling
- Priority modeling
- Implementation
- Modeling systems in BIP
- Discussion

Interaction modeling

• A ***connector*** is a set of ports which can be involved in an interaction

• Port attributes **(*complete*, *incomplete*)** are used to distinguish between rendezvous and broadcast.

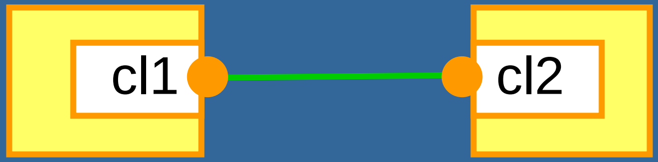
• An ***interaction*** of a connector is a set of ports such that: either it contains some complete port or it is maximal.



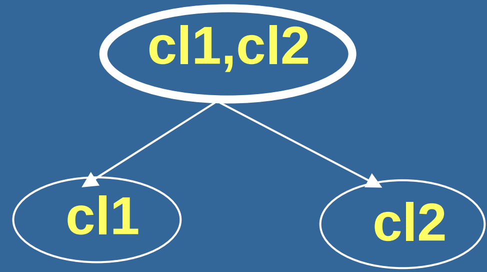
Interactions:

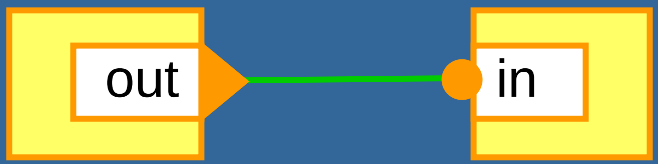
{tick1,tick2,tick3} {out1} {out1,in2} {out1,in3} {out1,in2, in3}

Interaction modeling - Examples

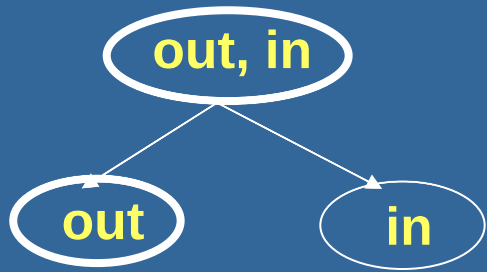


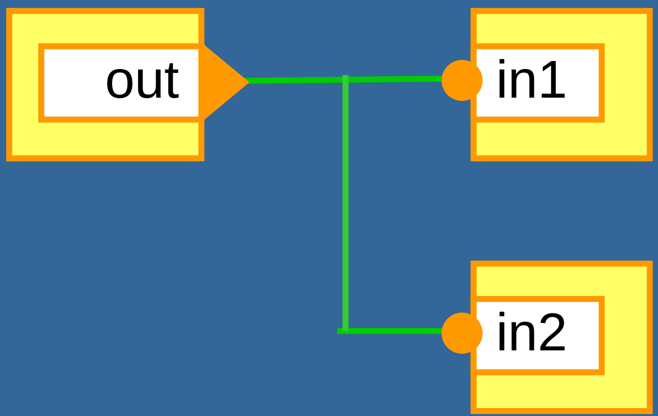
CN:{cl1,cl2}
CP: ∅



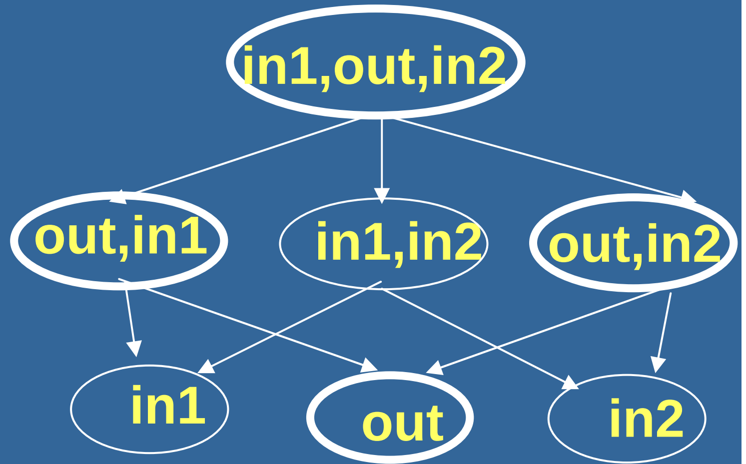


CN:{out,in}
CP: {out}

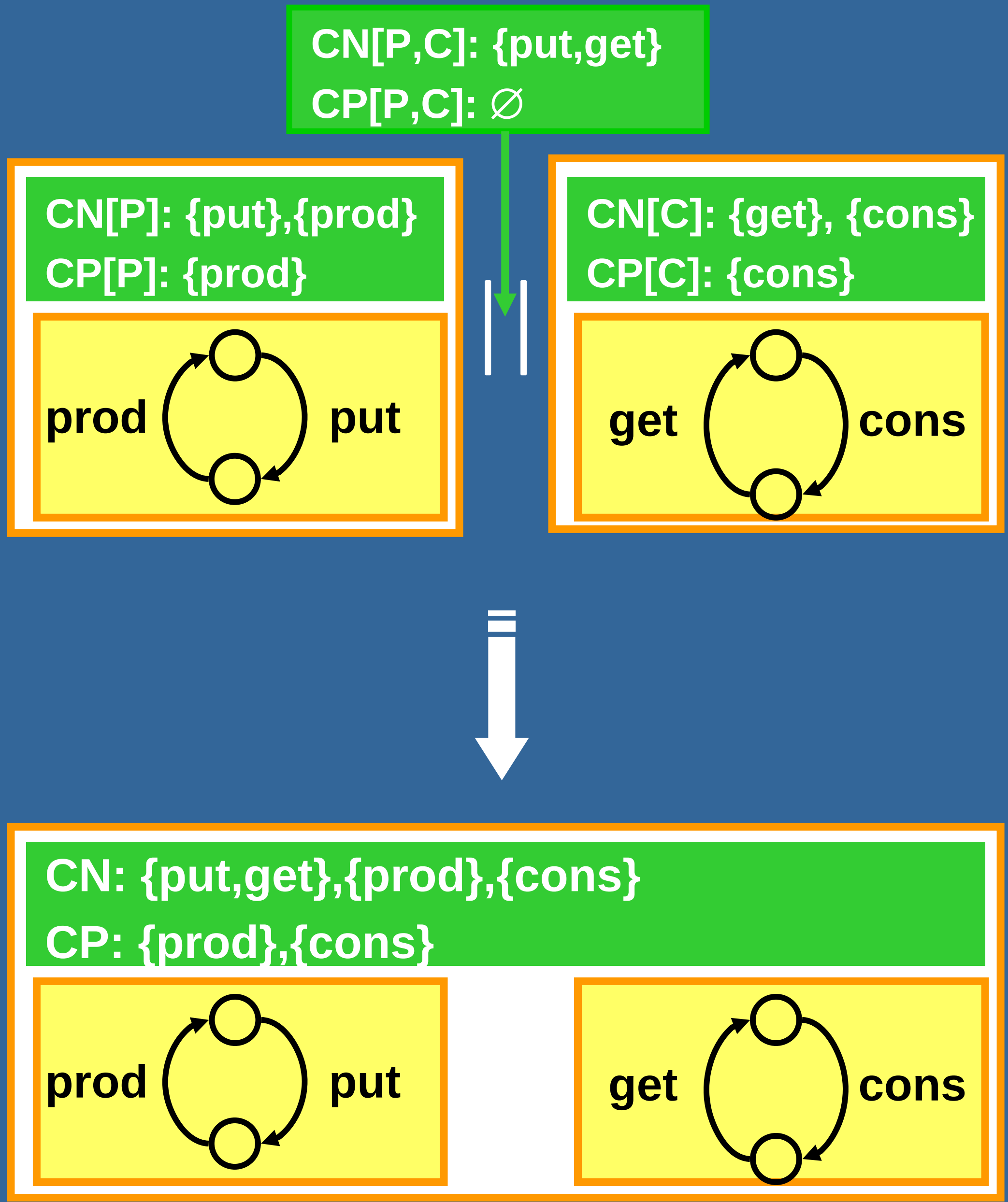




CN:{in1,out,in2}
CP: {out}



Interaction modeling – Composition



Interaction modeling – Data transfer

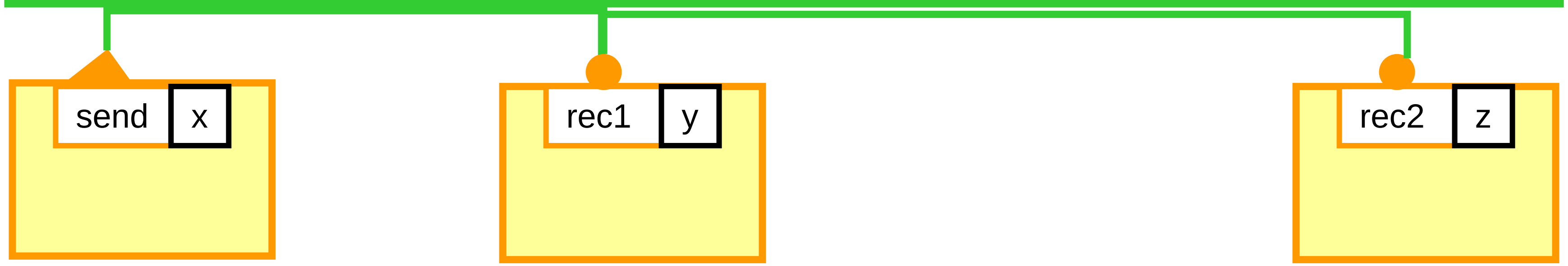
CN: BUS={send,rec1,rec2}

{send}: true →skip

{send,rec1}: x<y →x:=y-x, y:=y+x

{send,rec2}: x<z →x:=z-x, z:=z+x

{send,rec1,rec2}: x<z+y →x:=y+z-x, y:=y+x, z:=z+x



- Notice the difference between control flow and data flow (input, output)
- Maximal progress: execute a maximal enabled interaction

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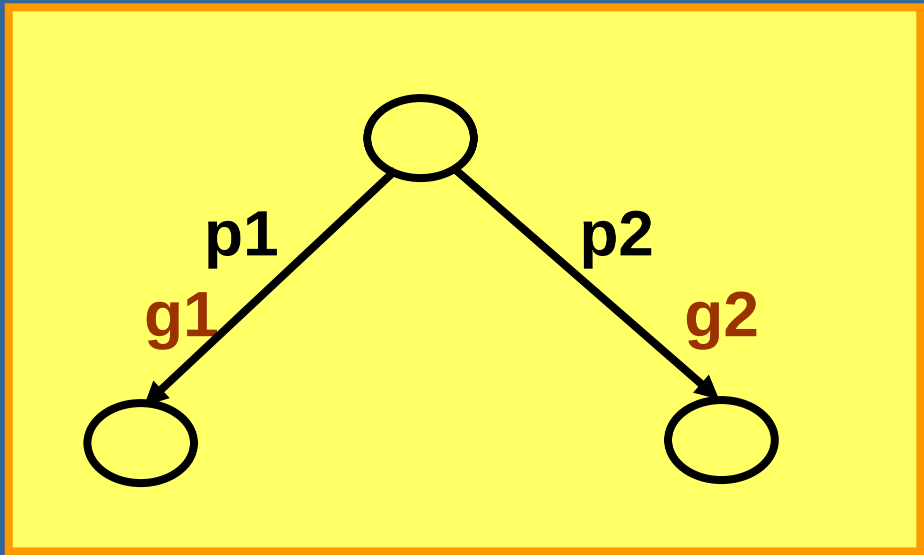
Priorities

Priorities are a powerful tool for restricting non-determinism:

- they allow straightforward modeling of urgency and scheduling policies for real-time systems
- run to completion and synchronous execution can be modeled by assigning priorities to threads
- they can advantageously replace (static) restriction of process algebras

Priorities - Definition

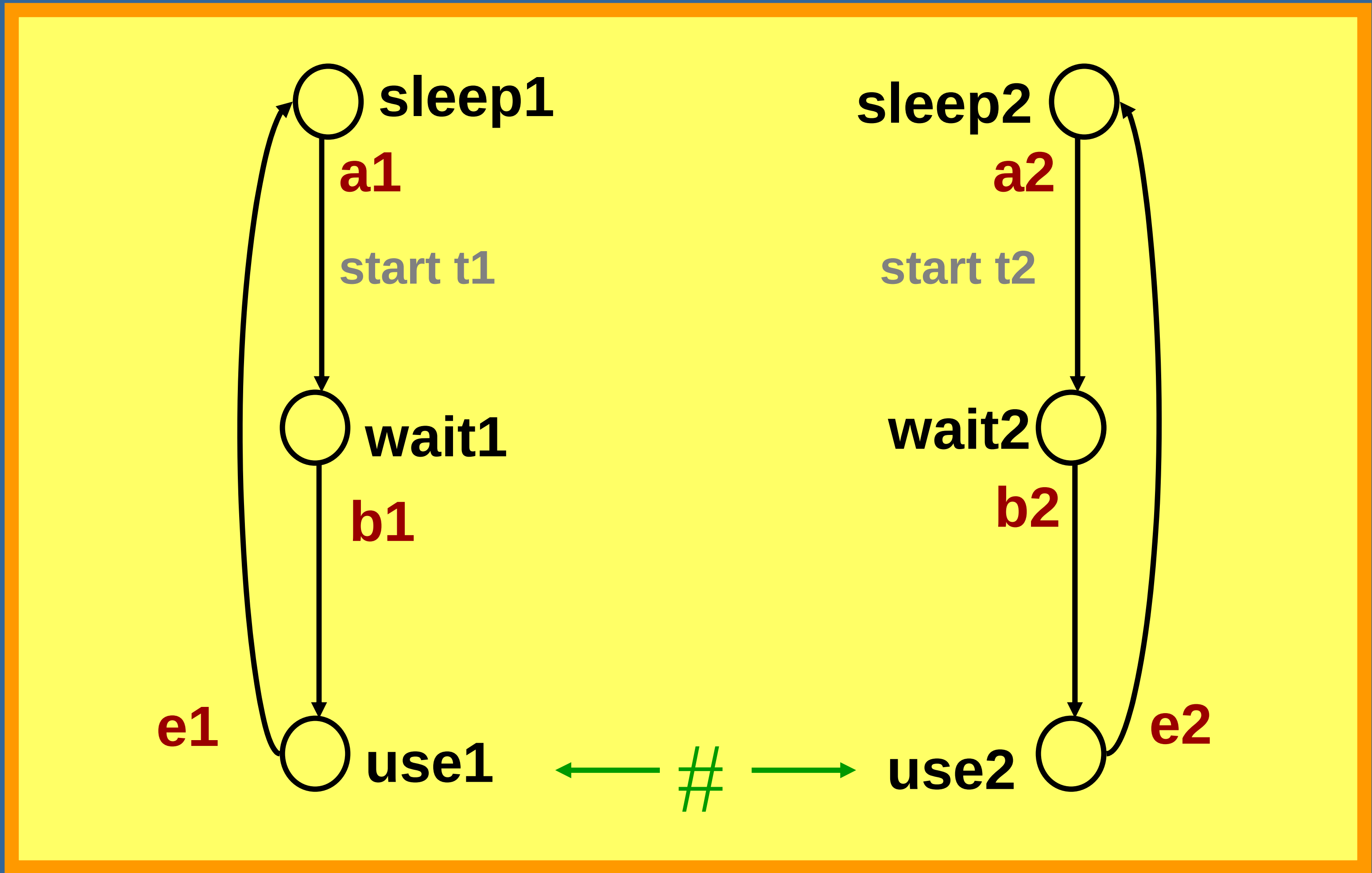
Priority rules



Priority rule	Restricted guard g1’
true $\rightarrow$ p1 $\langle$ p2	g1’ = g1 $\wedge \neg$ g2
C $\rightarrow$ p1 $\langle$ p2	g1’ = g1 $\wedge \neg$(C $\wedge$ g2)

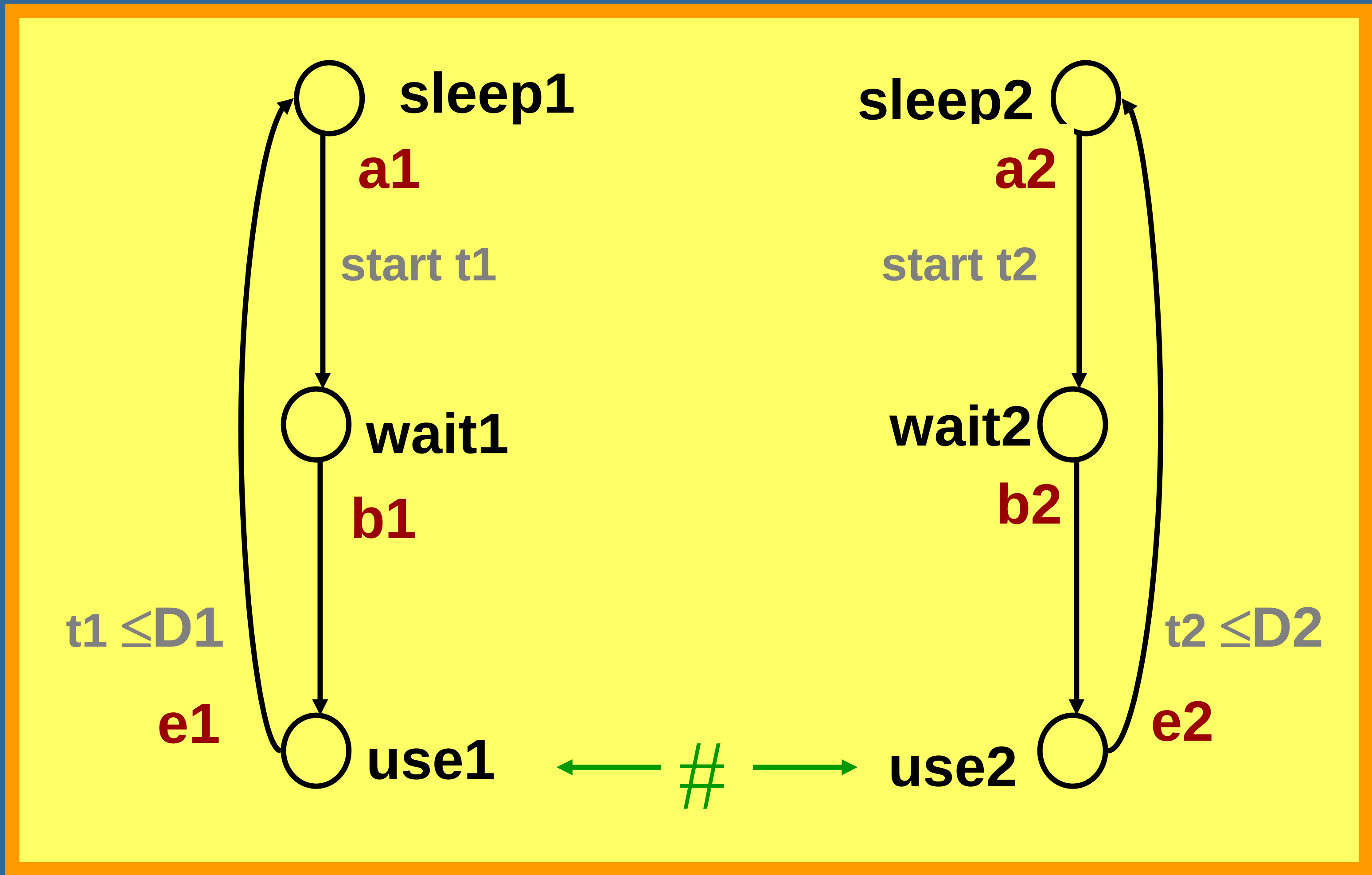
Priorities – Example: FIFO policy

$t1 \leq t2 \rightarrow b1 \langle b2$ $t2 < t1 \rightarrow b2 \langle b1$

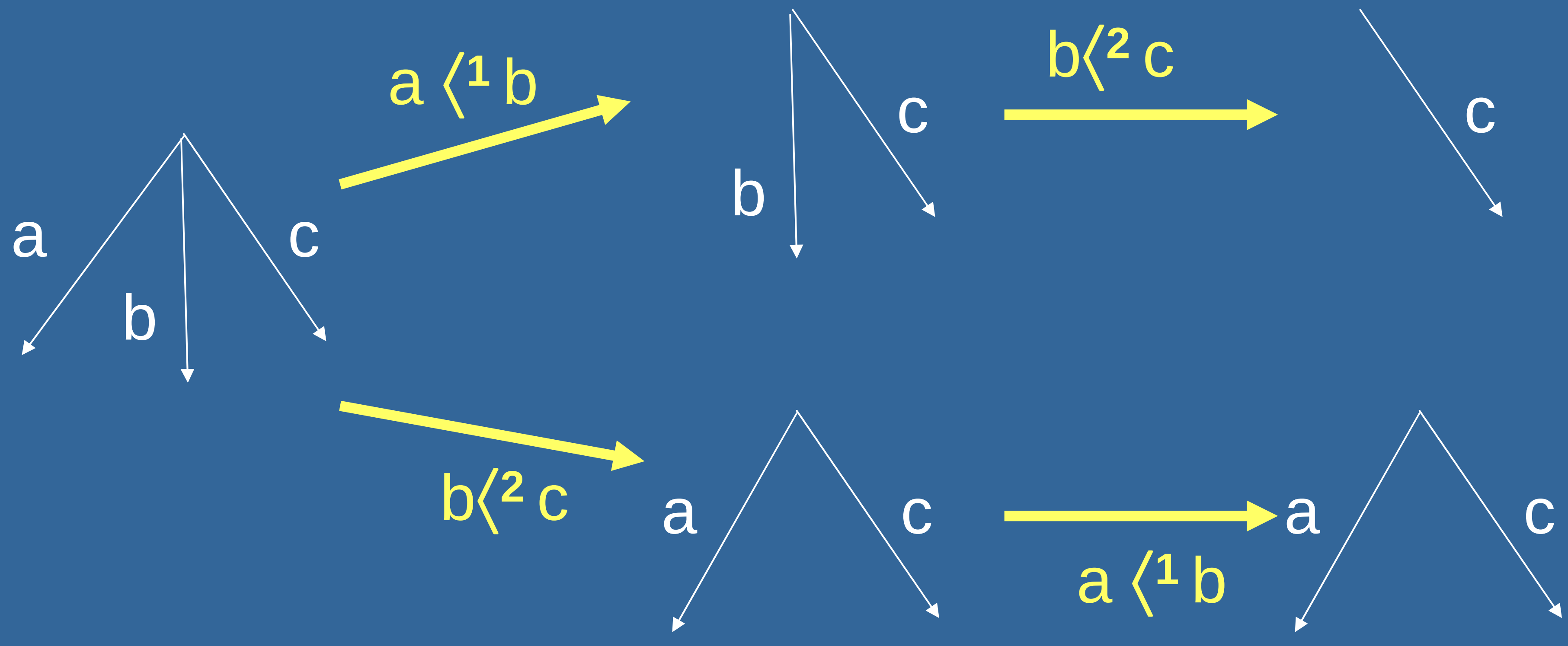


Priorities – Example: EDF policy

$D1\text{-}t1 \leq D2\text{-}t2 \rightarrow b2 \langle\, b1$ $D2\text{-}t2 < D1\text{-}t1 \rightarrow b1 \langle\, b2$

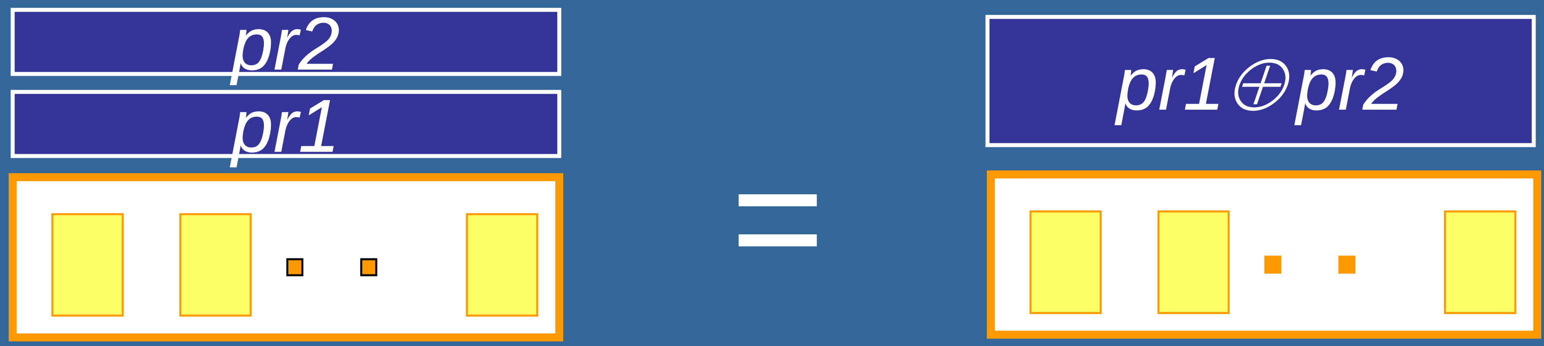


Priorities – Composition



Priorities – Composition (2)

Take:



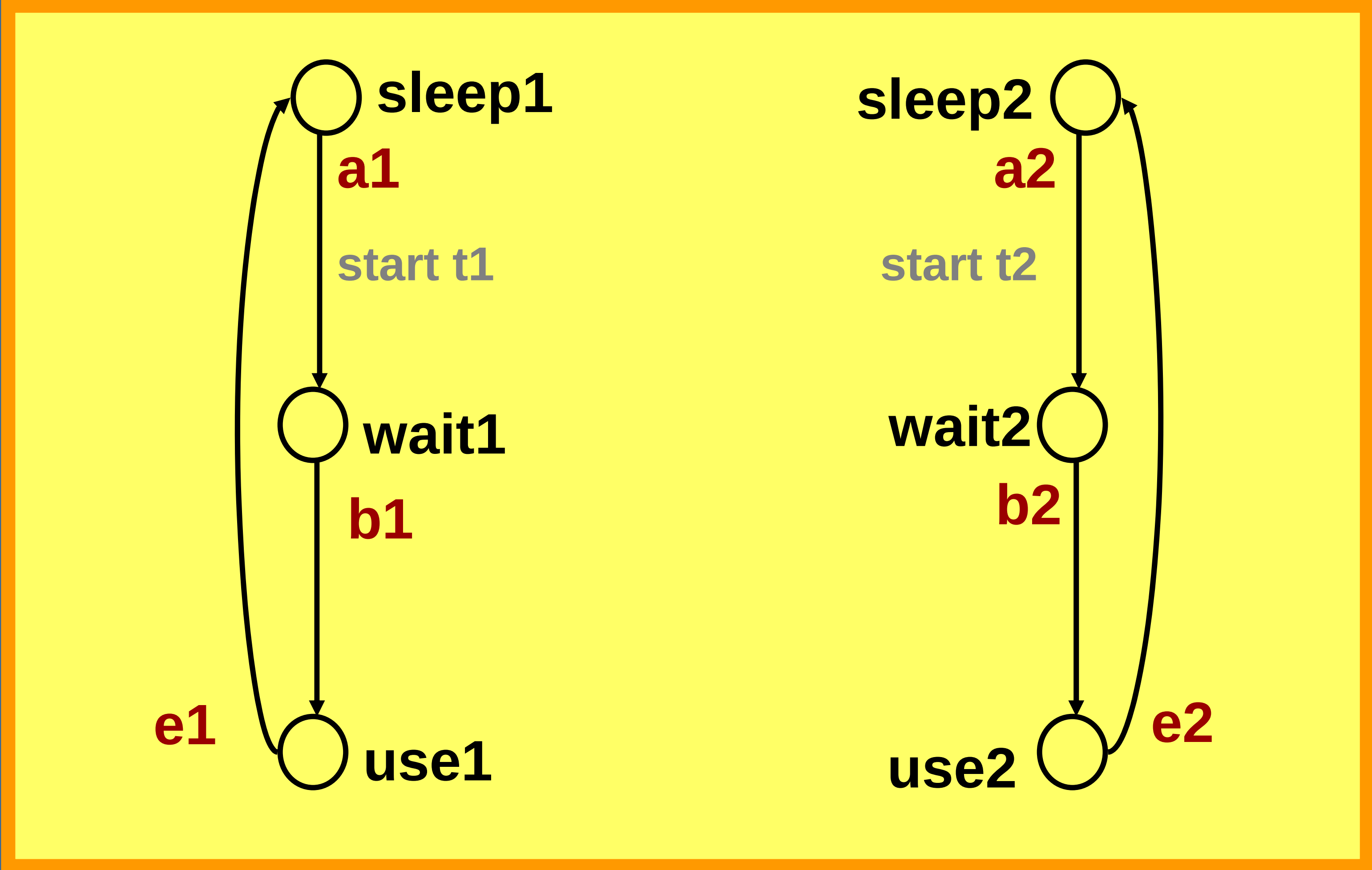
pr1⊕ pr2 is the least priority containing pr1∪pr2

Results :

- The operation ⊕ is partial, associative and commutative
- pr1(pr2(B)) ≠pr1(pr2(B))
- pr1⊕ pr2(B) *refines* pr1∪pr2(B) *refines* pr1(pr2(B))
- Priorities preserve deadlock-freedom

Priorities – Example: Mutual exclusion + FIFO policy

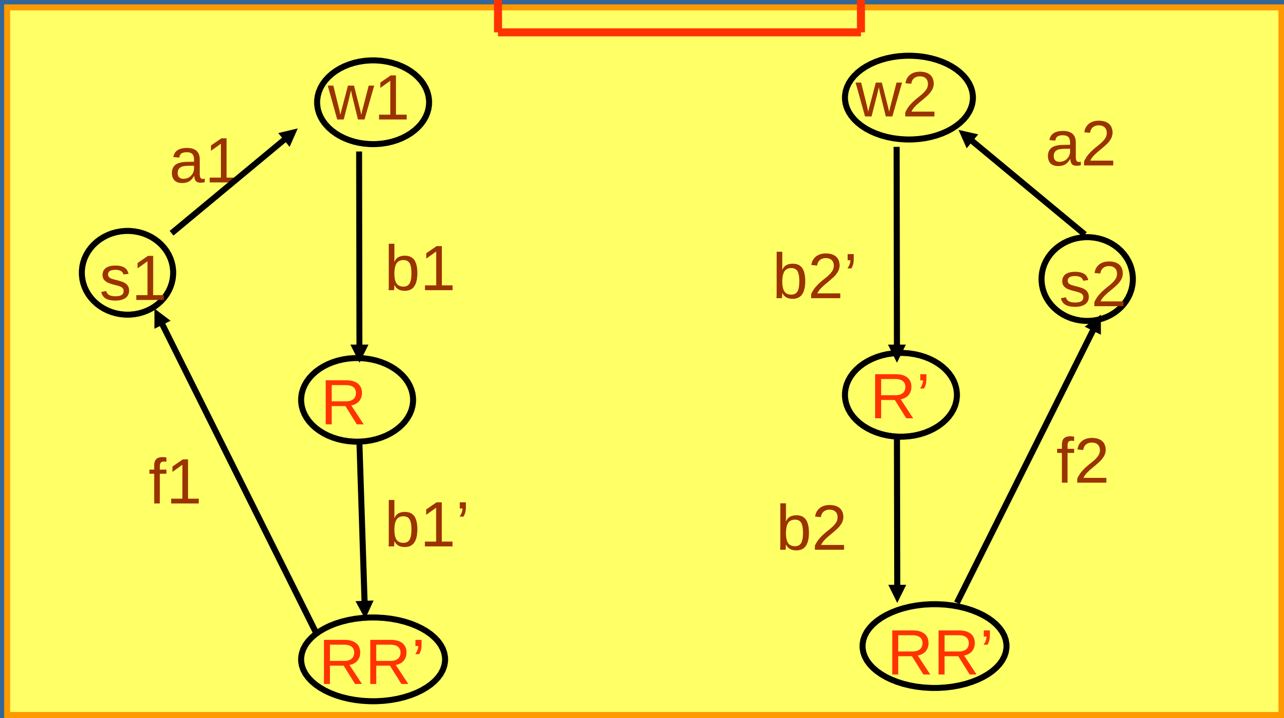
t1≤ t2 → b1⟨ b2	t2< t1 → b2⟨ b1
true → b1⟨ e2	true → b2⟨ e1



Priorities – Checking for deadlock-freedom: Example

Mutex on R’ : b1 ⟨ f2 b2 ⟨ { f1, b1’}

Mutex on R : b1’ ⟨ { f2, b2 } b2’ ⟨f1



Risk of deadlock: b1’ ⟨ b2 and b2 ⟨ b1’

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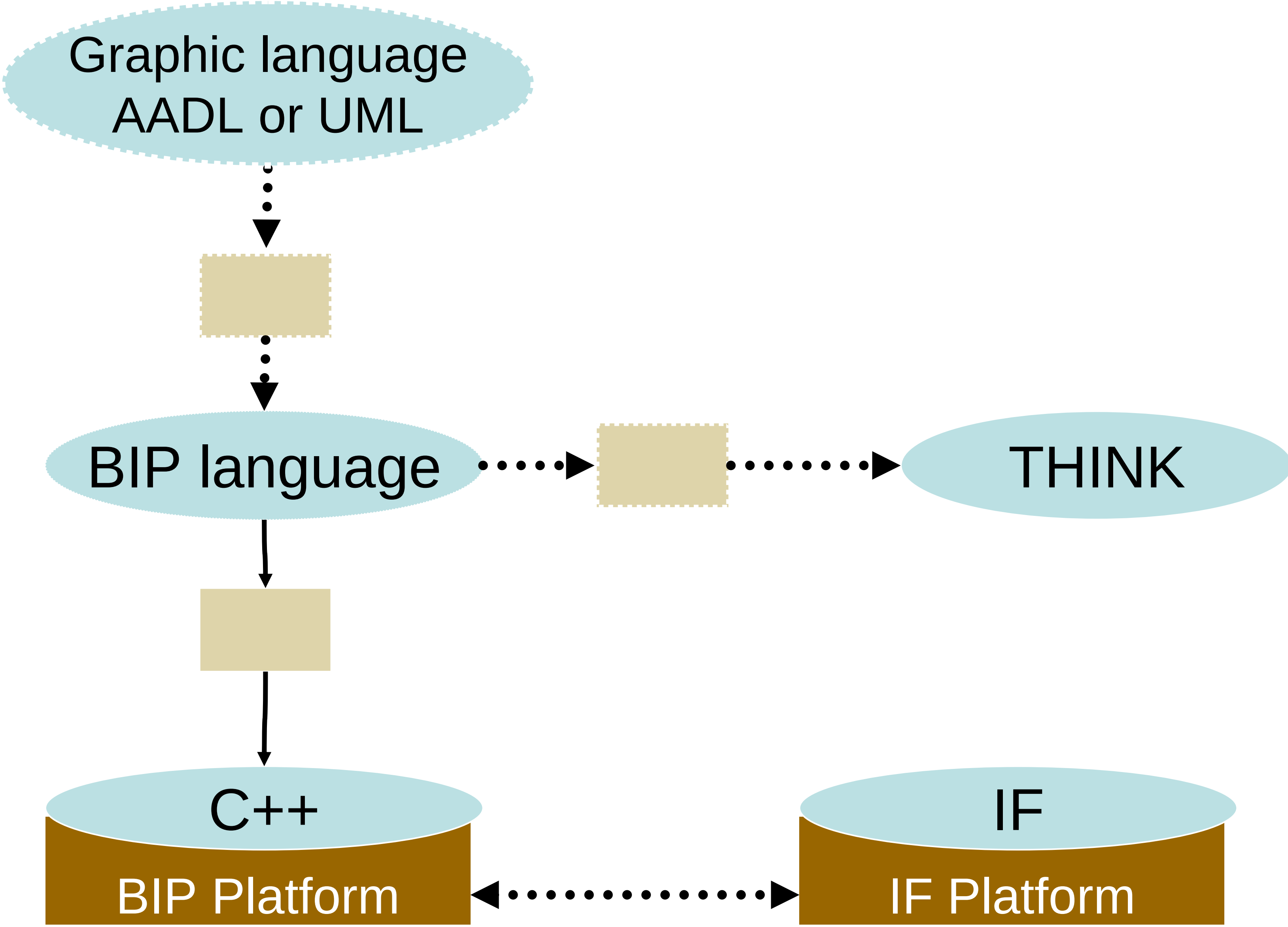
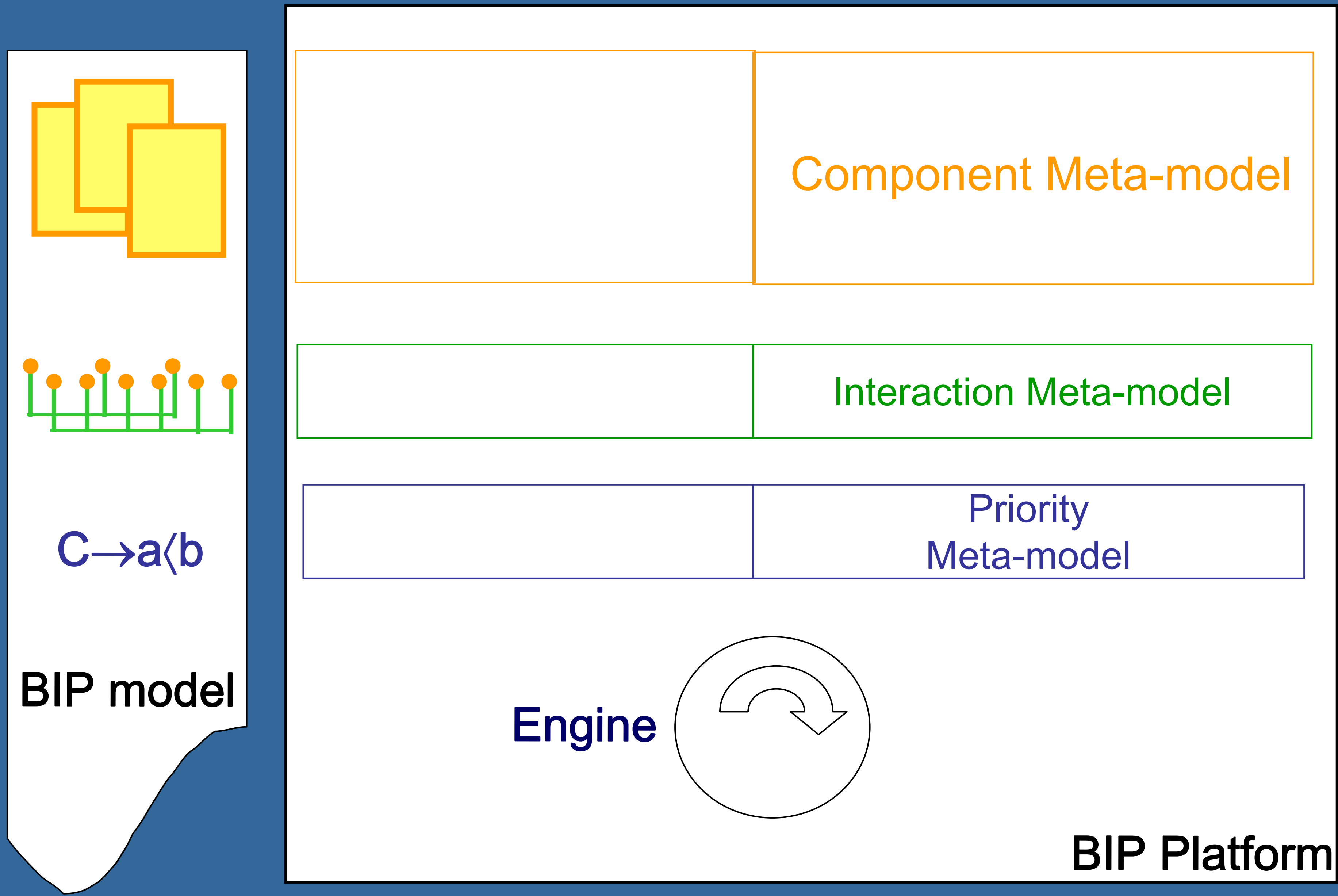
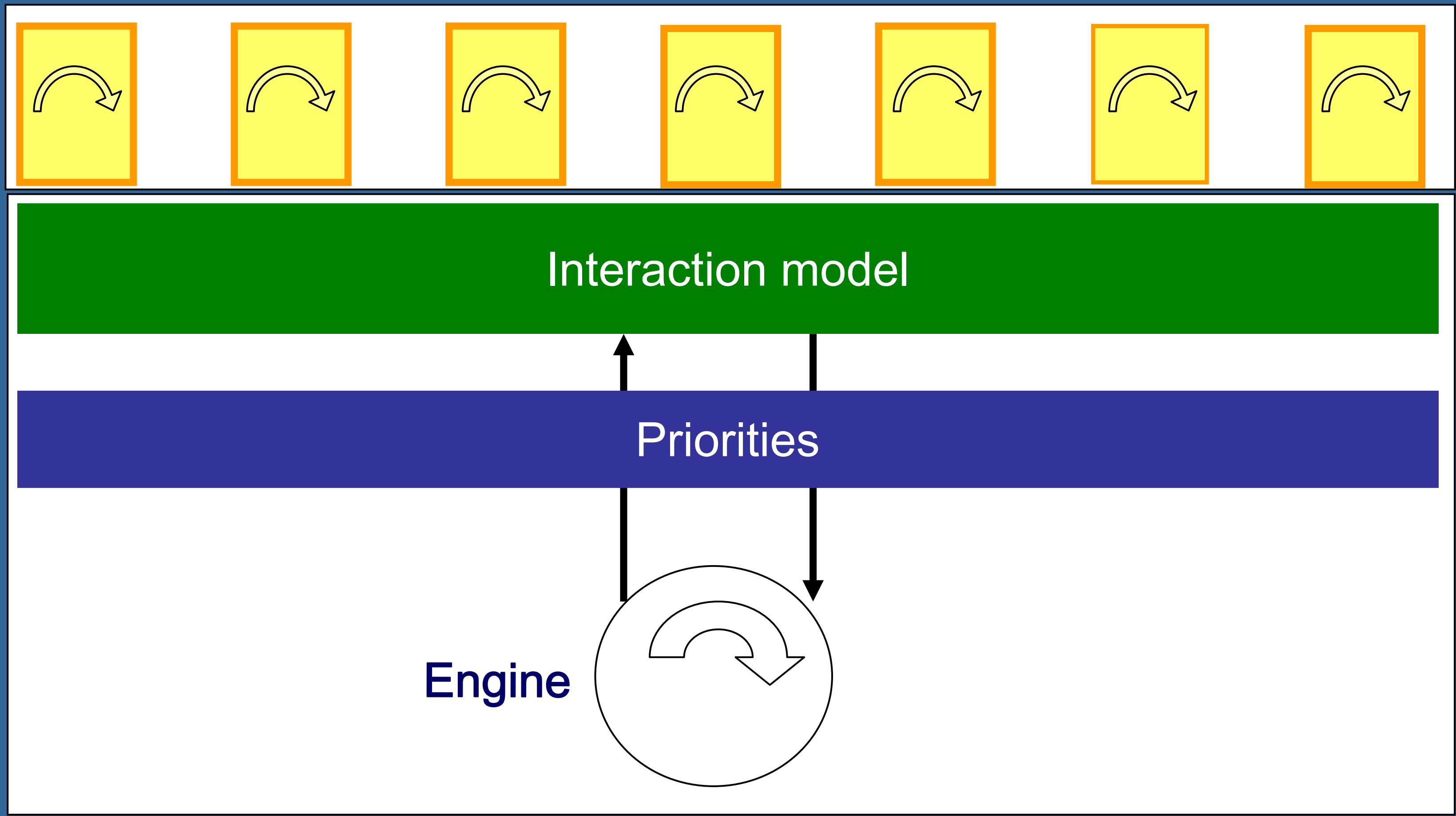
Implementation – the BIP toolset



Implementation – C++ code generation for the BIP platform

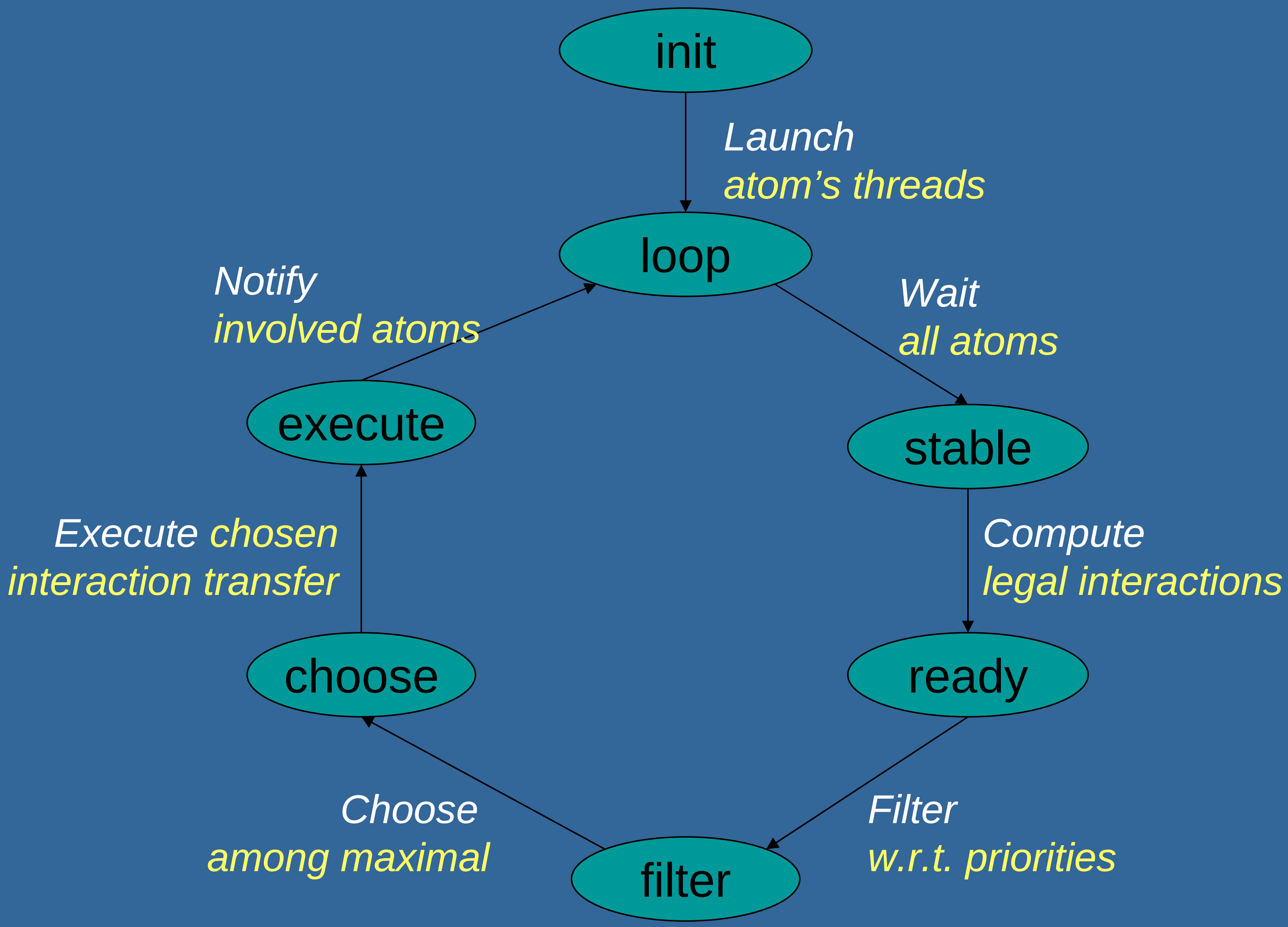


Implementation – The BIP platform



- Code execution and state space exploration features
- Implementation in C++ on Linux using POSIX threads

Implementation – The BIP platform: The engine



Implementation – the BIP language: atomic component

```
component C
port  complete: p1, … ;  incomplete: p2, …
data  {# int x, float y, bool z, …. #}
init {# z=false; #}
   behavior
          state s1
                    on p1 provided g1 do f1 to  s1'
                    ………………       ……
                    on pn provided gn do fn to  sn'

          state s2
                    on …..
            ….

          state sn
                    on ….
   end
end
```

Implementation – the BIP language: connectors and priorities

connector BUS= {p, p', … , }
complete()
  behavior
    on $\alpha 1$ **provided** $g_{\alpha 1}$ **do** $f_{\alpha 1}$
    ……….
    on αn **provided** $g_{\alpha n}$ **do** $f_{\alpha n}$
  end

priority PR
    if C1 ($\alpha 1 < \alpha 2$), ($\alpha 3 < \alpha 4$) , …
    if C2 (α < …), (α <…) , …
    …
    if Cn (α <…), (α <…) , …

Implementation – the BIP language: compound component

```
component name
    contains c_name1 i_name1(par_list)
        ……
    contains c_namen i_namen(par_list)

    connector name1
    ……
    connector namem

    priority name1
    ……
    priority namek
    end
```

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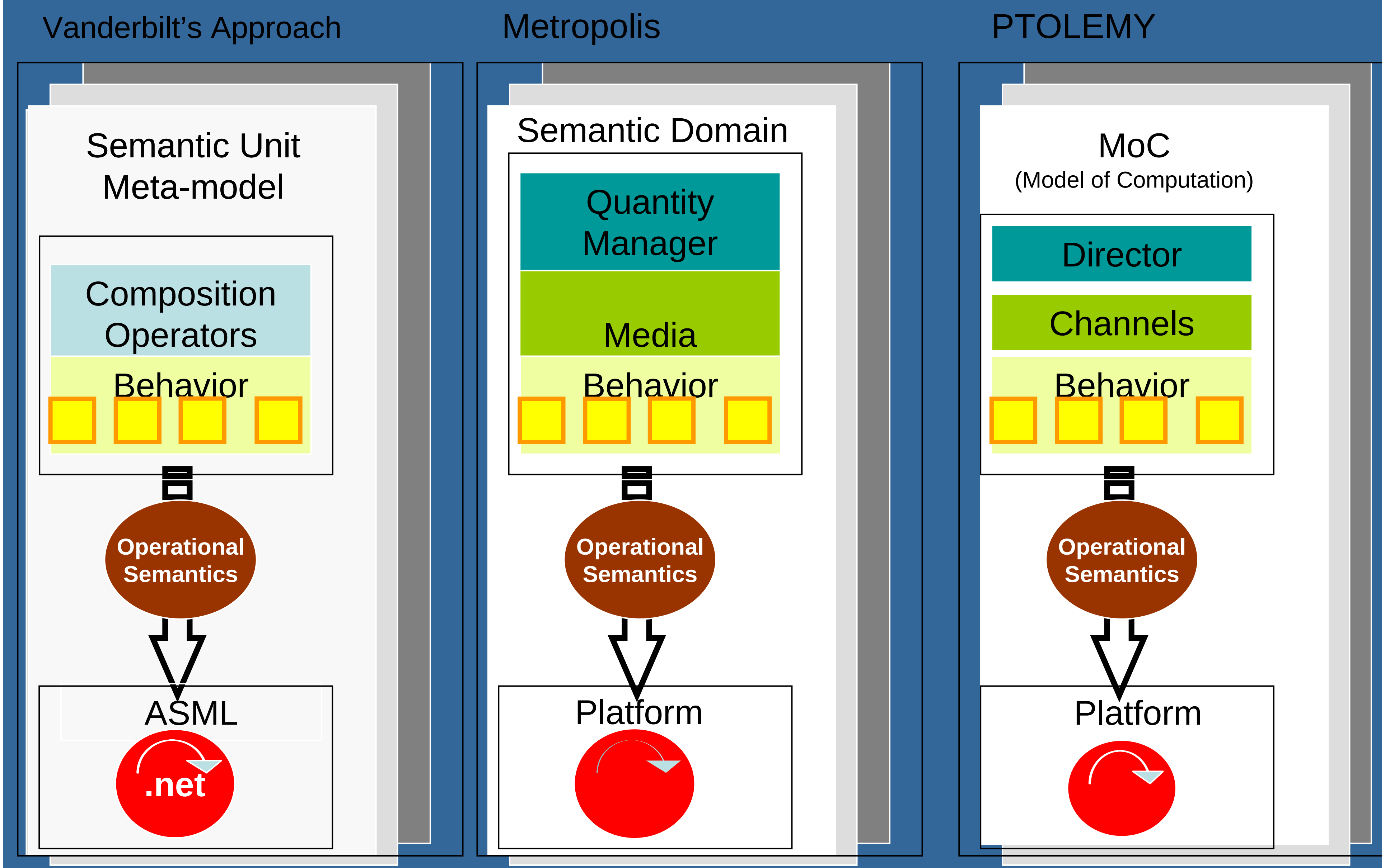
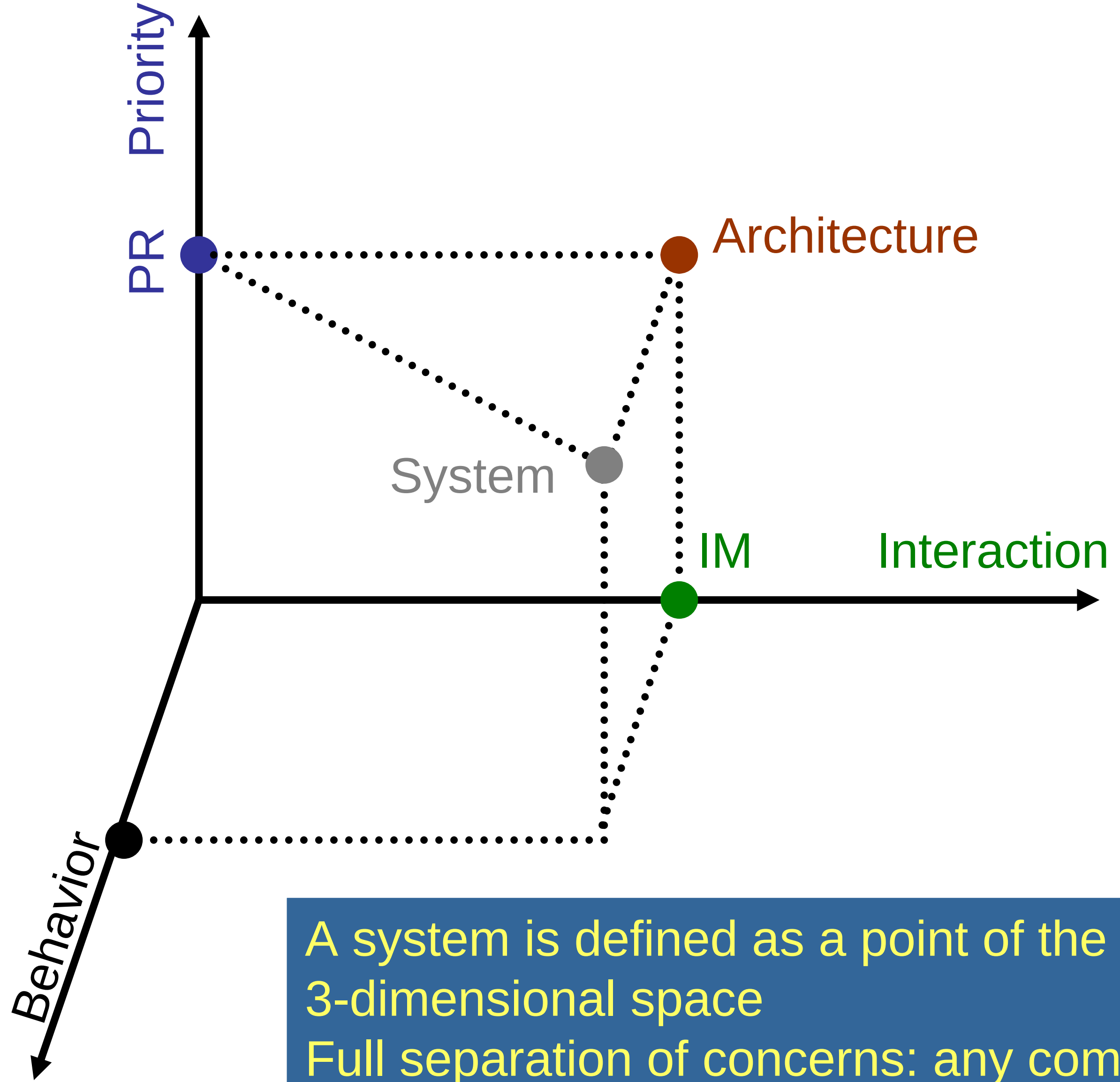
Modeling in BIP– Other approaches encompassing heterogeneity

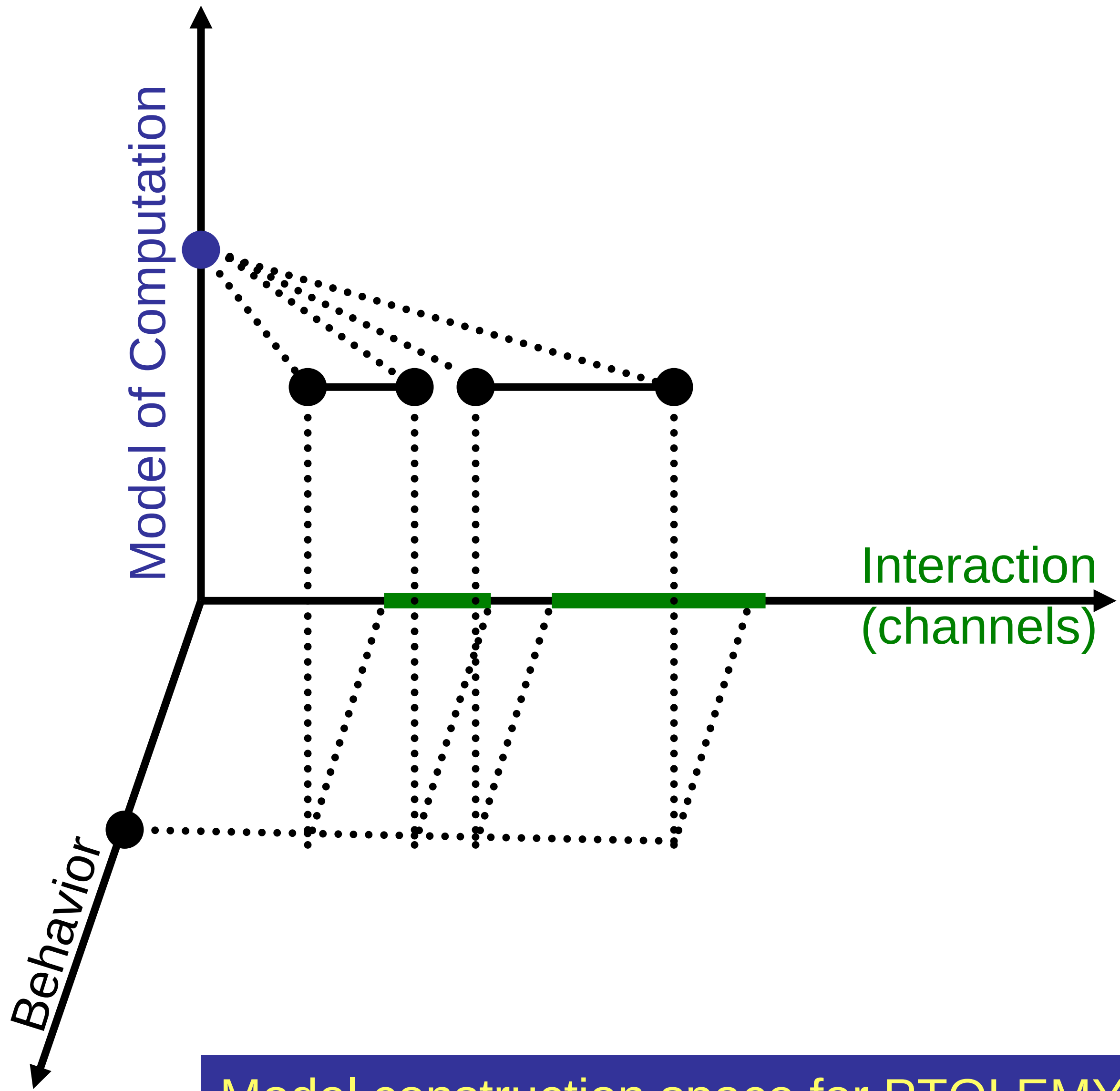


Modeling in BIP– Model construction space



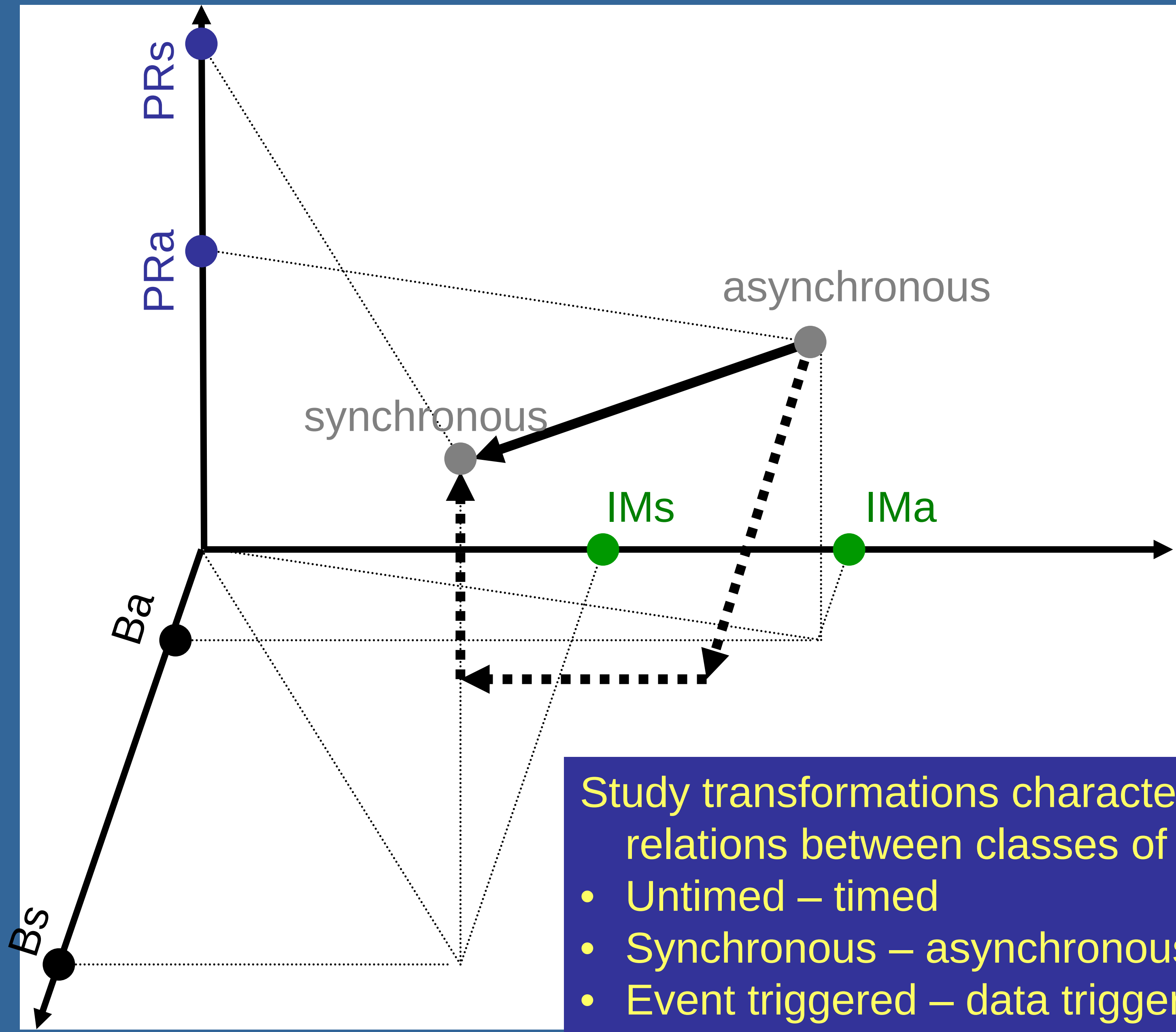
A system is defined as a point of the 3-dimensional space
Full separation of concerns: any combination of coordinates defines a system

Modeling in BIP – Model construction space (2)



Model construction space for PTOLEMY

The BIP framework – Relating classes of components

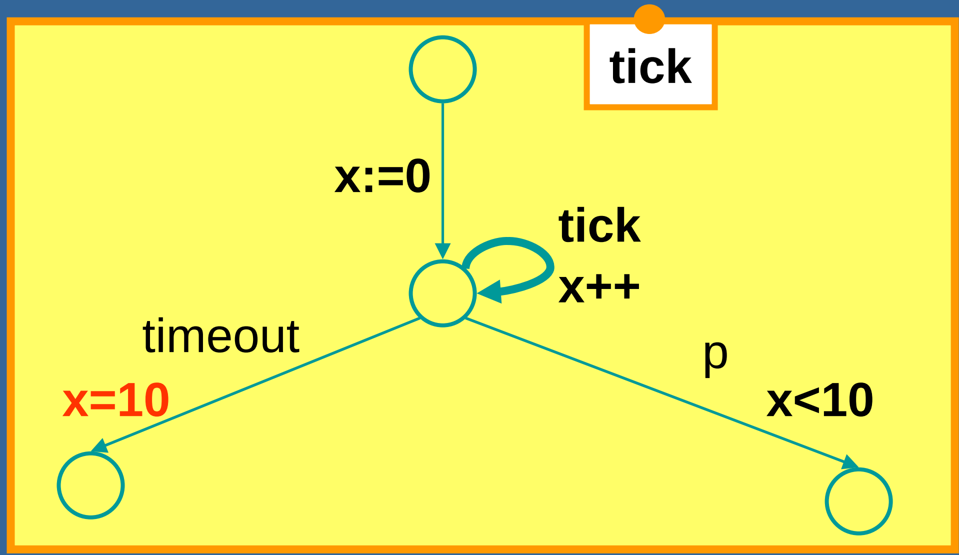


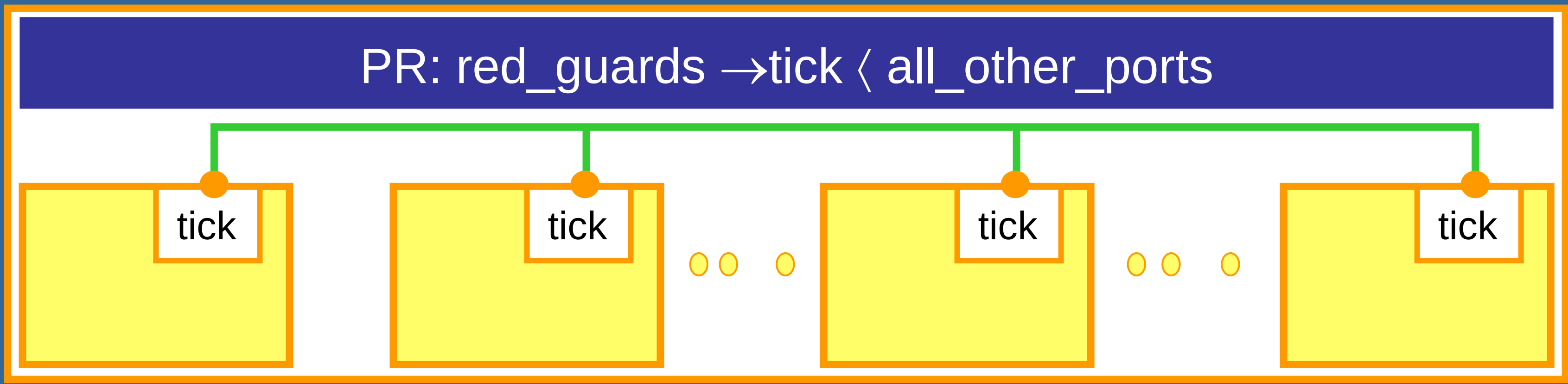
Study transformations characterizing relations between classes of systems:

- Untimed – timed
- Synchronous – asynchronous
- Event triggered – data triggered

Modeling in BIP – Timed systems

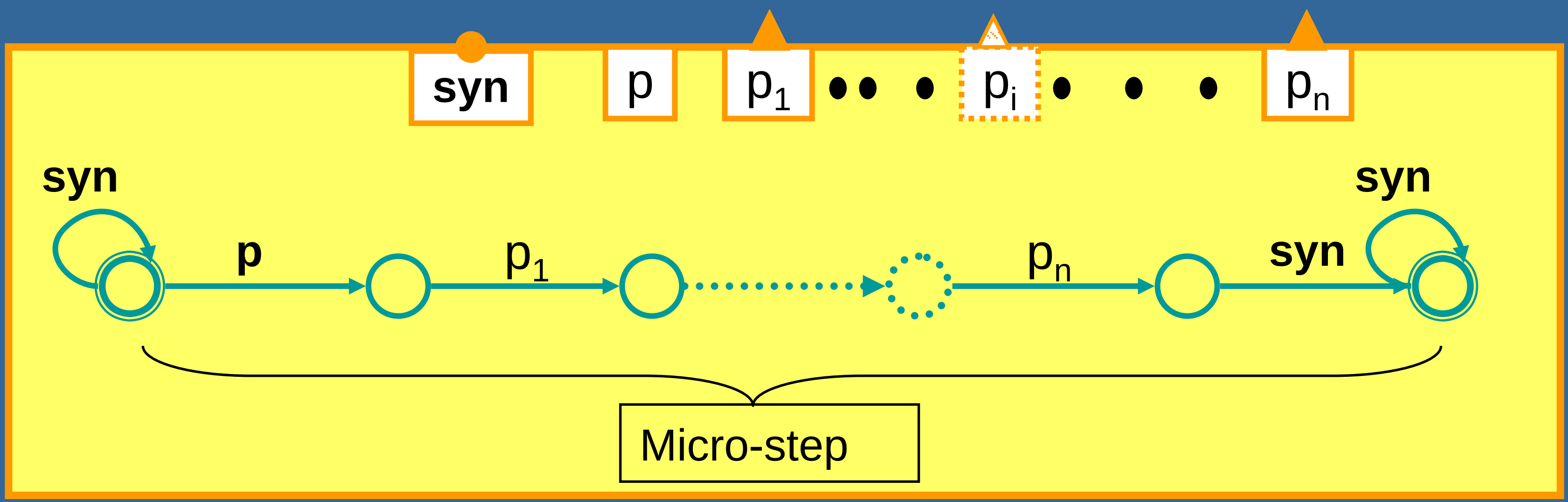
Timed Component



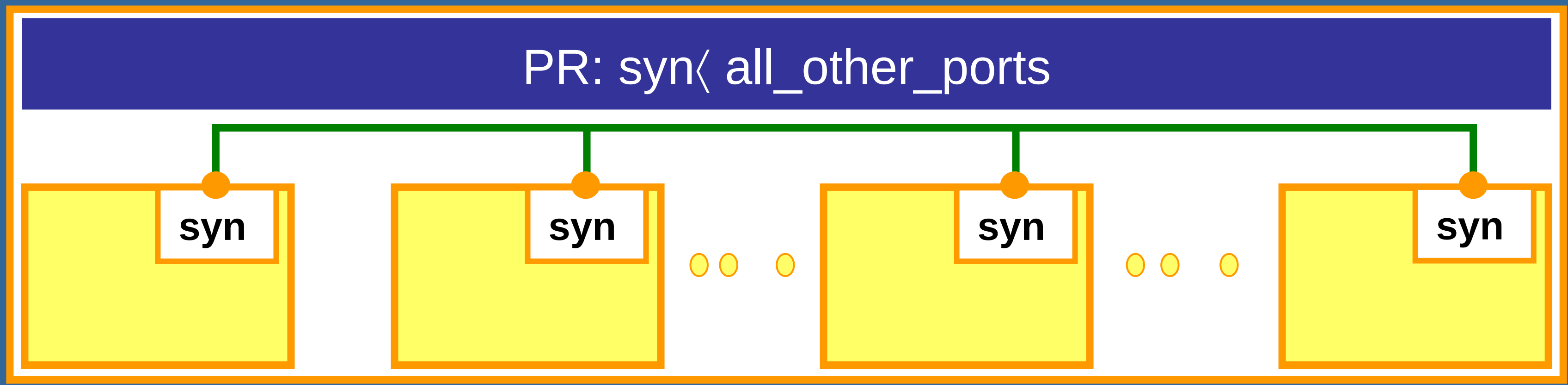


Timed architecture

Modeling in BIP – Synchronous systems



Synchronous component



Synchronous architecture

Modeling in BIP – MPEG4 Video encoder: Componentization

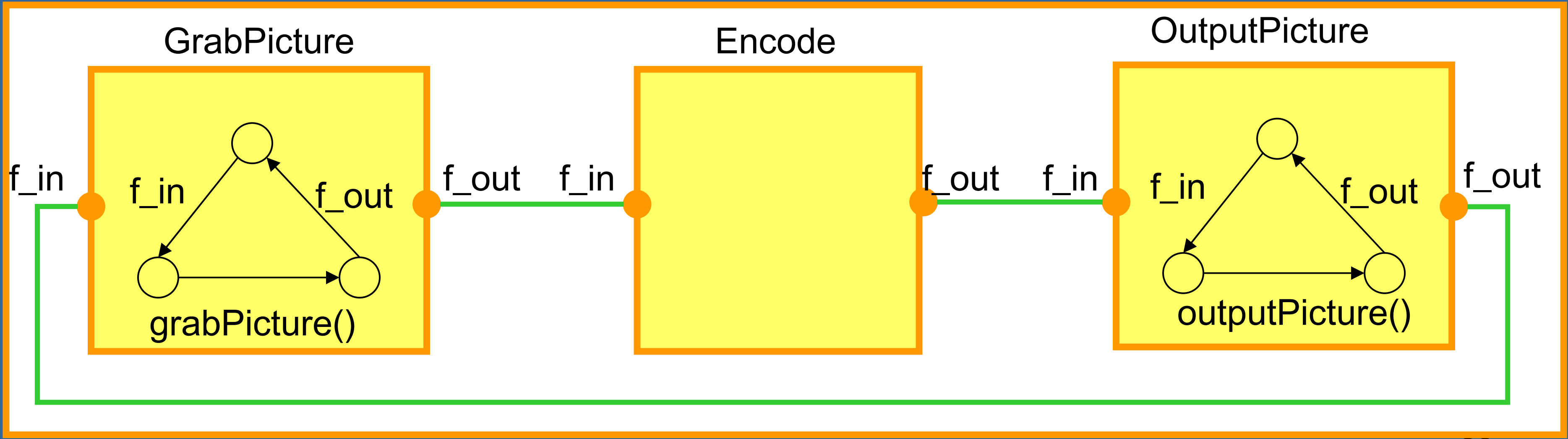
Transform a monolithic program into a componentized one

++ reconfigurability, schedulability

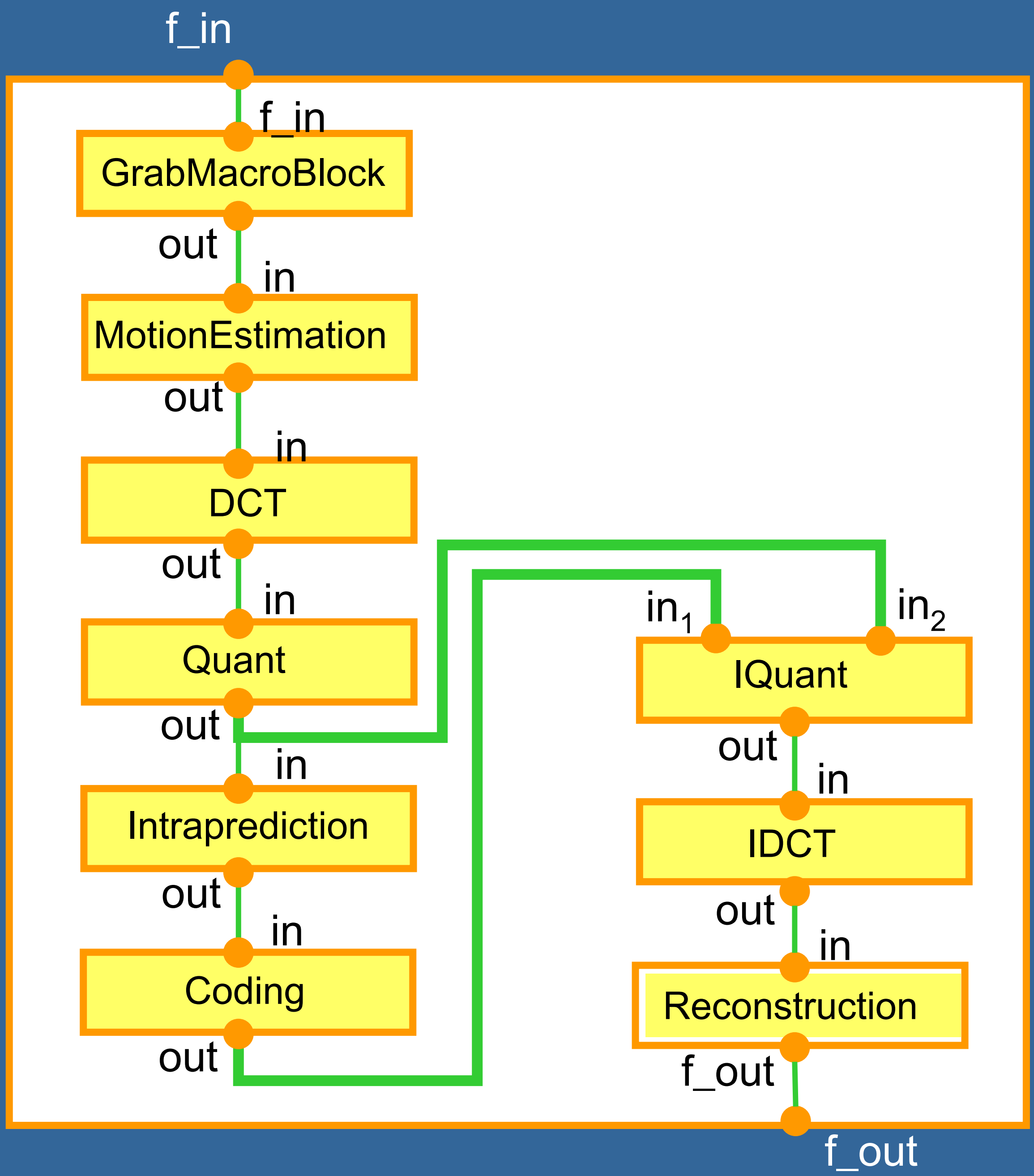
– – overheads (memory, execution time)

Video encoder characteristics:

- 12000 lines of C code
- Encodes one frame at a time:
  - grabPicture() : gets a frame
  - outputPicture() : produces an encoded frame



Modeling in BIP –Video encoder: The Encode component

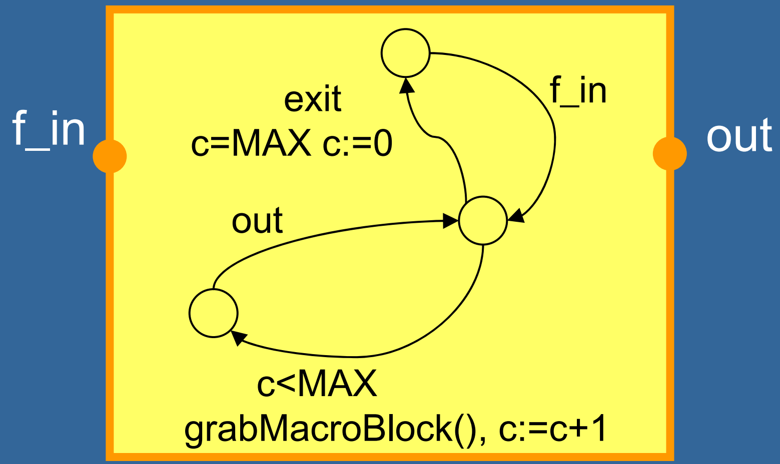


GrabMacroBlock: splits a frame in (W*H)/256 macro blocks, outputs one at a time

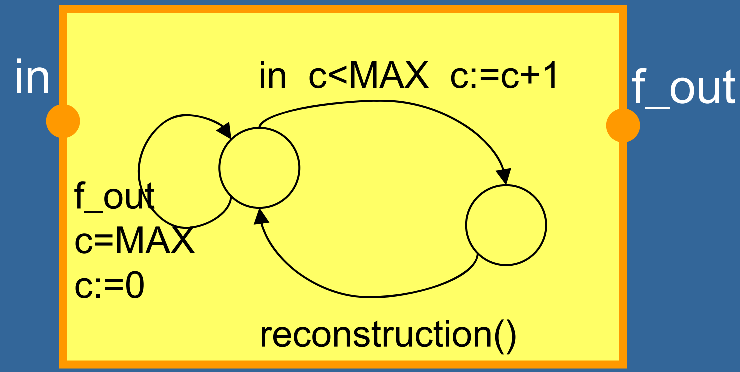
Reconstruction: regenerates the encoded frame from the encoded macro blocks.

: buffered connections

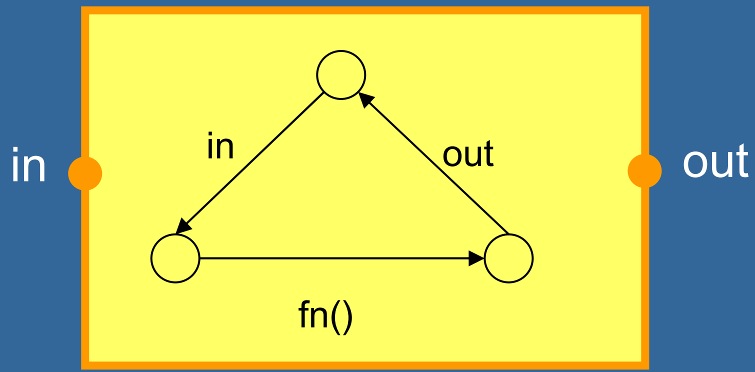
Modeling in BIP – Video encoder : Atomic components



GrabMacroBlock



Reconstruction



Generic Functional component

MAX=(W*H)/256
W=width of frame
H=height of frame

Modeling in BIP – Video encoder: The BIP Encoder features

- BIP code describes a control skeleton for the encoder
  - Consists of 20 atomic components and 34 connectors
  - ~ 500 lines of BIP code
  - Functional components call routines from the encoder library
- The generated C++ code from BIP is ~ 2,000 lines
- The size of the BIP binary is 288 Kb compared to 172 Kb of monolithic binary.

Modeling in BIP – Video encoder : Componentization overhead

Overhead in execution time wrt monolithic code:

- ~66% due to communication (can be reduced by composing components at compile time)
  - function calls by atomic components to the execution engine for synchronization.
- ~34% due to resolution of non determinism (can be reduced by narrowing the search space at compile time)
  - time spent by engine to evaluate feasible interactions

Problem: Reduce execution time overhead for componentized code

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Discussion – The BIP framework: summary

Framework for component-based construction encompassing heterogeneity and relying on a **minimal set of constructs and principles**

Clear separation between structure (interaction +priority) and behavior

- Structure is a first class entity
- Layered description => separation of concerns => incrementality
- Correct-by-construction techniques for deadlock-freedom and liveness, based (mainly) on sufficient conditions on the structure

Discussion - The BIP framework: Work directions (1)

Methodology

- Modeling: BIP as a programming model, reference architectures in BIP
- Implementation techniques

BIP toolset

- Generation of BIP models from system description languages such as SysML (IST/SPEEDS project), AADL and SystemC (ITEA/Spices project)
- Model transformation techniques in particular for code optimization
- Validation techniques
  - connection to Verimag's IF simulation/validation environment
  - specific techniques e.g. checking conditions for correctness by construction

Discussion – The BIP framework: Work directions (2)

Theory

- Study Component Algebras CA= (**B**, GL,⊕, ≅), where
  - (GL,⊕) is a monoid and ⊕ is idempotent
  - ≅ is a congruence compatible with operational semantics

- Study notions of **expressiveness** characterizing structure**:** Given two component algebras defined on the same set of atomic components,

  CA1 **is more expressive** than CA2

  if $\forall P \;\; \exists gl2 \in GL2 \; gl2(B1, .,Bn) \text{ sat } P \Rightarrow \exists \; gl1 \in GL1. \; gl1(B1, \ldots Bn) \text{ sat } P$

- Model transformations
  - relating classes of systems
  - preserving properties

- Distributed implementations of BIP

More about BIP:

- http://www-verimag.imag.fr/index.php?page=tools
- Email to Joseph.Sifakis@imag.fr

THANK YOU