MIMOS a Framework for Design and Update

of Real-Time Embedded Systems

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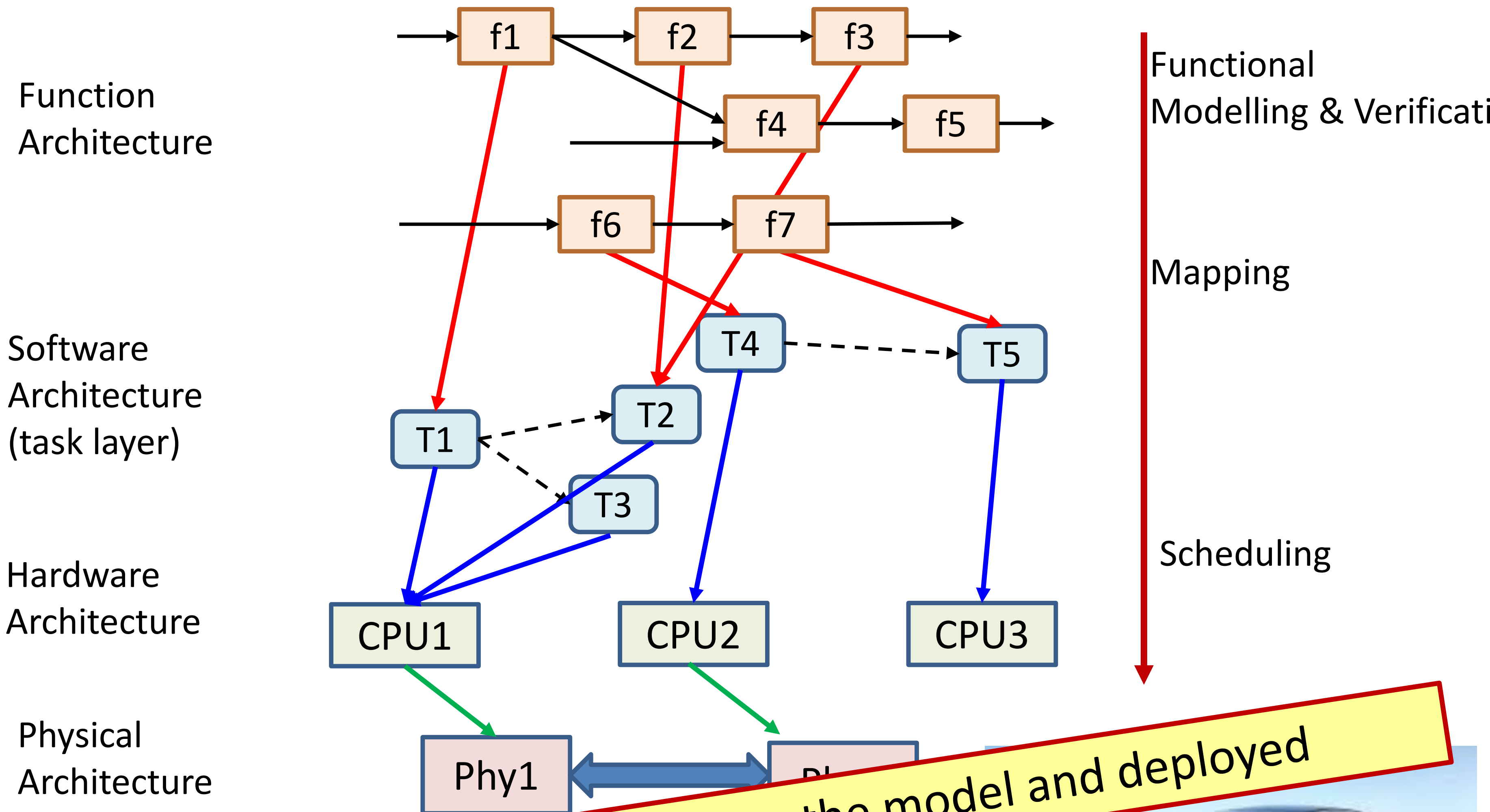
2 supporting projects:

CUSTOMER: Customizable Embedded Real-Time Systems: Challenges & Key Techniques (Wang Yi‘s ERC)

UPDATE: Desgined for Update of Next-Generation Embedded Systems (Knut & Alice Wallenberg Foundation)

both until end of 2026

Model-Based Design of Real-Time Systems



Code running on HW: generated from the model and deployed

Model-based Update

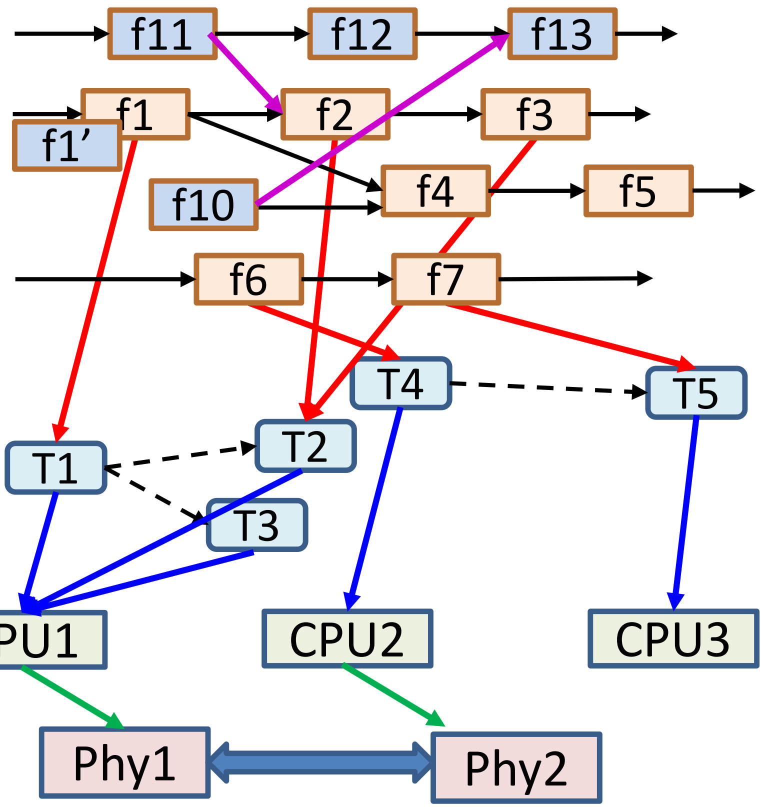
Update in this picture ?

Function update: change/upgrade functions, add new functions, eliminate, reconnect …

Approach: contract-based

Design challenge:

- composability
- Support for impact analysis
- independence of time and function



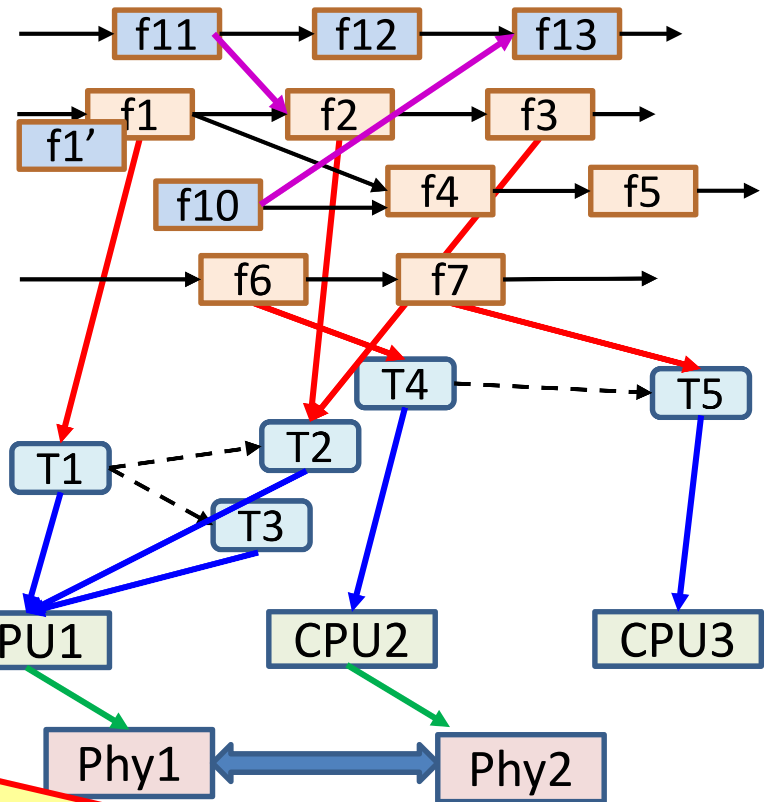
Model-based Update

Update in this picture ?

“Software” update:

Can we guarantee that

- small changes at function layer lead to small changes at software layer ?
- Small increase of workload leads to small resource usage inc
- Efficient … updates (container based)
- ….



Encouraging initial results, first implementations

Challenge: Resource-Efficiency

- Keeping track of workload and available resources
- Dynamic scheduling and schedulability analysis
- Architecture challenges: multicores, distributed …

OUTLINE

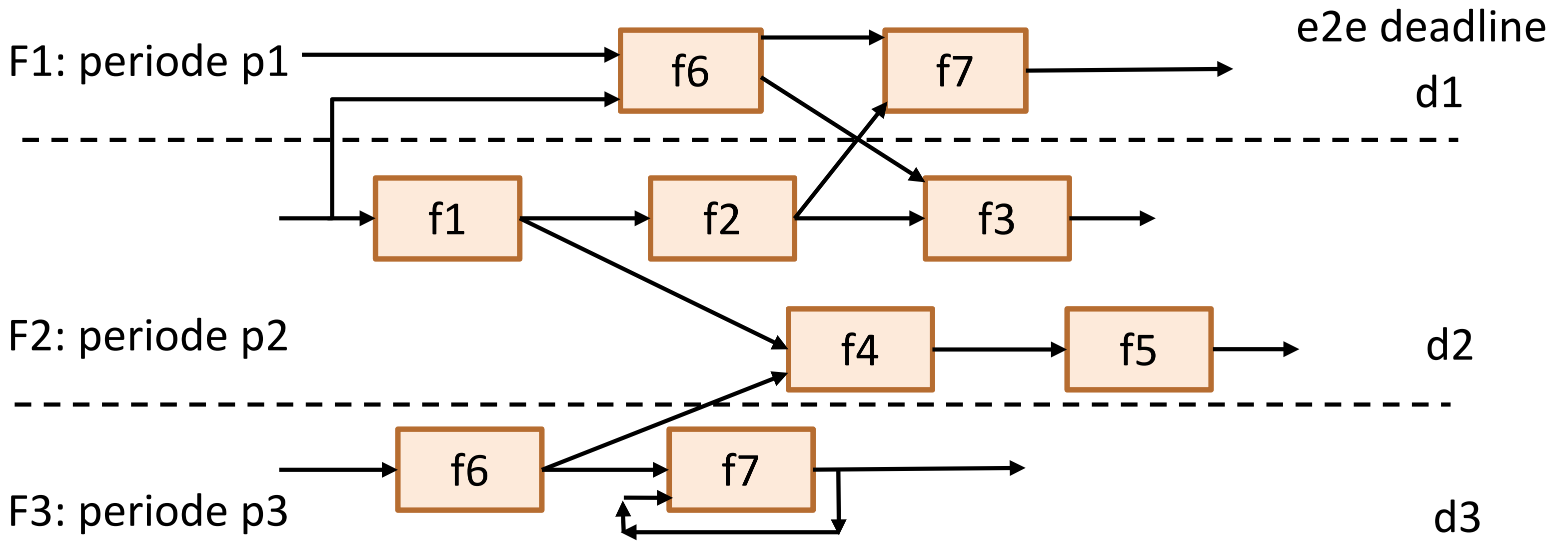
1. Motivations: on Design and Update of Real-time systems

2. System Design in MIMOS
   - Requirements on the design language
   - Our design language

3. A Type system for MIMOS
   - Boundedness as type correctness

4. Contracts for MIMOS
   - Some reflections on property specification and verification at the function layer

Function Design



Functions: **Streams** (& Memory) → **Streams**

Hierarchically defined

Requirements:

- **Determinism** is fundamental
- Separation of Concern: Abstraction
  - **Independence of timing and functionality**
- Updatability/Composability
  - Avoidance of interference & Resilience
  - Asynchronous Communication (non-blocking)

Function Design and Verification:

Synchronous (Scade, Lustre, Synchronous Data-Flow, …)

Advantages:

- Deterministic
- Time and function reasonably independent
- (Mostly) easy to design
- Easy to simulate and verify

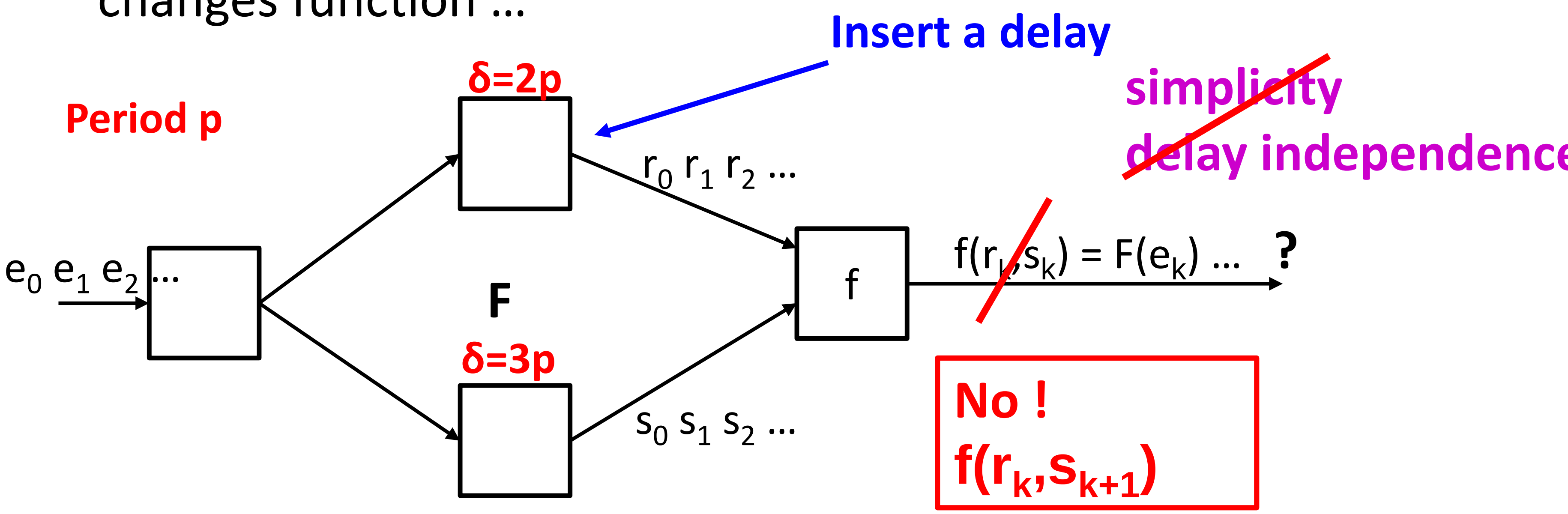
Software level: "**Virtually Synchronous**" : semantic preserving mapping to a task set run asynchronously on OS / middleware

- TTA (Timed Triggered Architecture) – single rate [HK&al 90ies]
- PALS (Physically Asynchronous Logically Synchronous) [JM&al 09]
- Recent LF (Lingua Franca) Reactor Model [EL&al 2019]

Why do we need something different ?

There are problems: synchronous is

- Very good for single rate (computation within period, communication between periods)
- Can be adapted to multi-rate (some loss of simplicity)
- Problematic for **deadline > period** ... can be done but delay changes function ...

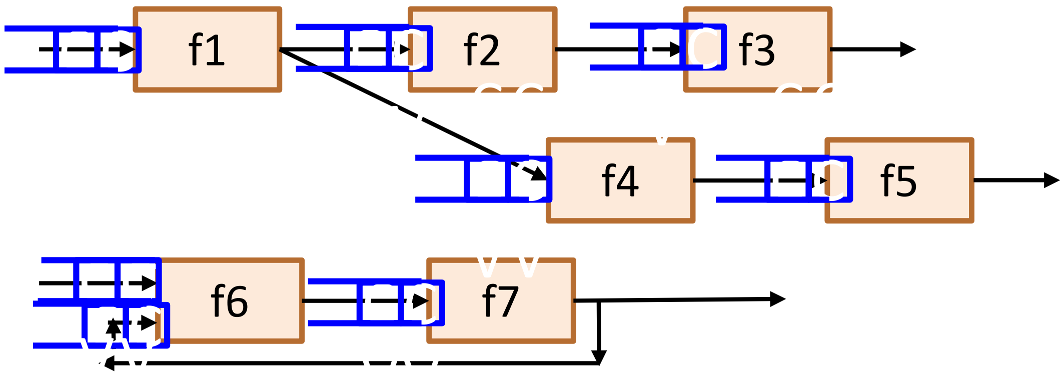


Kahn Process Networks (KPN)

Paper: “The semantics of a simple language for parallel programming”, Gilles Kahn, 1974

Semantics of KPN: stream transformation as a fix point

Operational model for KPN



A network of processes

- Communicating through (potentially unbounded) FIFO buffers
- Read (and compute a step): when all required data is in the FIFOs (blocking, similar to PetriNets)
- Write: non-blocking (asynchronous)

Properties of KPN

- **Determinism**: a KPN defines a function from input streams to output streams
  - independent of the execution orders/scheduling
  - Independent of computation/communication delays
- Boundedness of FIFOs ? undecidable in the general case (expressiveness)

➢ MIMOS: Typed KPN will make it "tractable"

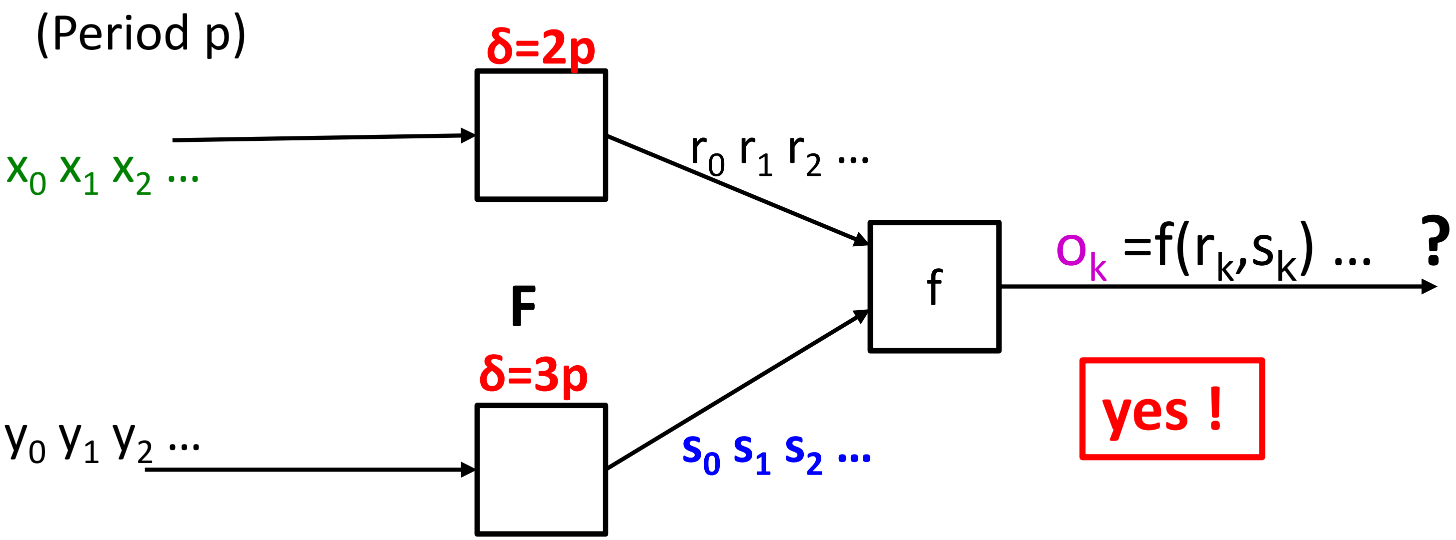
Observation: a synchronous program is a KPN with (very) strict constraints on execution order which guarantees: when a node is executed, FIFOs contain exactly the input to be read (→ no need for FIFOs)

KPN extended with timing constraints [YMG-Coordination-22]

- Nodes : real-time tasks with a period and a deadline (or possibly other recurring task release strategy).
- Execution rule:
  - Read input at release times (if present)
  - Write output at deadline (or relaxed "upto" deadline)
- Extensions (optimizations and resilience):
  - Registers : keep only the most recent value of a FIFO (synchronous)
  - "timed read" (efficient implementation of "sporadic" tasks, resilience)

Theorem: TKPN are deterministic functions from timed input to timed output streams

Observation: in many cases, no need for time stamps



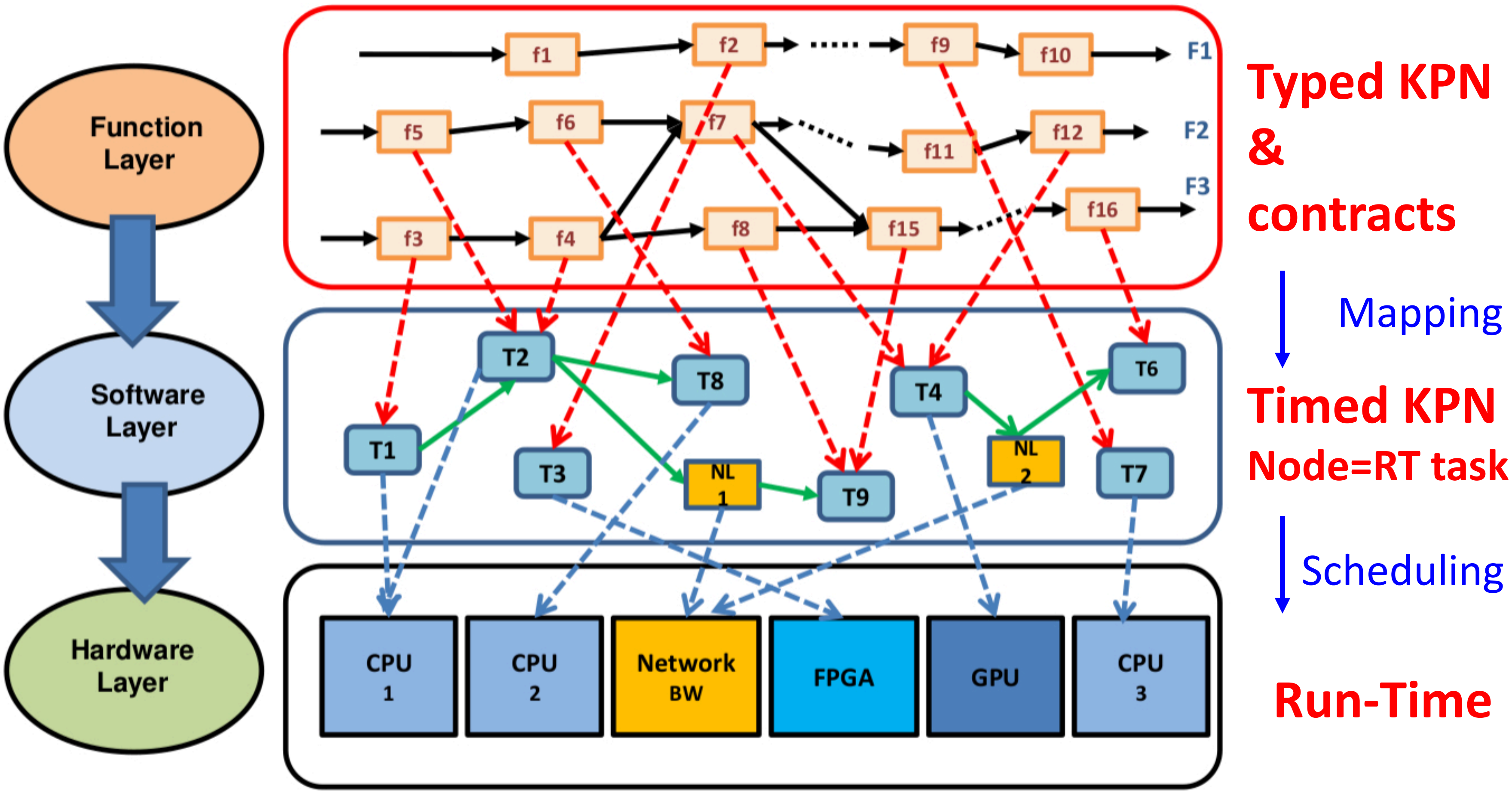
KPN solve the problem (by waiting for input)

Initial elements in buffers: e.g. in **s**: shorten (minimal) delay from **x** to **o** – by using “older” values of s (synchronous solution)

➔ **Tradeoff between delay and precision**

Deterministic: function does not depend on the actual delays

Model-based Design with MIMOS



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A type system for KPN

Why a type system ?

Remember: general form of a KPN “step function”:

Any program whose effect is (a) to read a finite number of elements from the FIFOs and (b) to write at most a finite number elements to its output and terminates

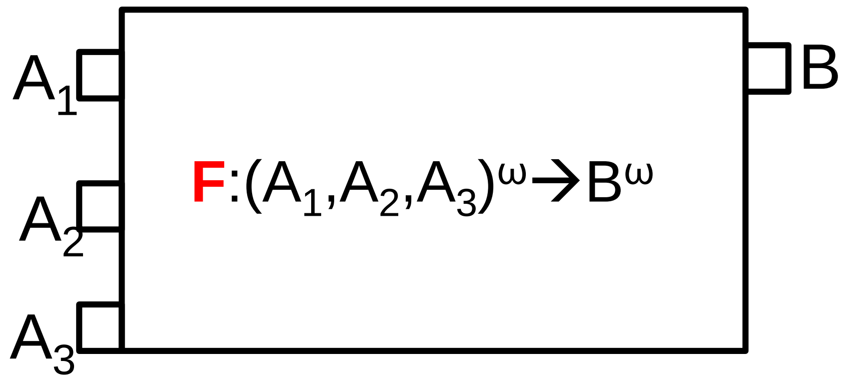
Problem:

- How man elements does the program read and write ?
- Does it terminate ?

To be able to give guarantees:

we must impose restrictions on such programs

A node: a typed function



Types:

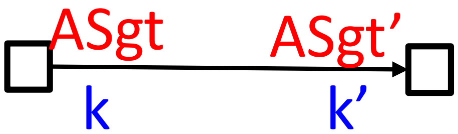
- Basic Type (BT): Bool, Natural, Real, Int, Tuple/Product, List ...
- (bounded) Segment (Sgt): BT^k, $BT^{\leq k}$
- Interface Type (IT): tuple(Sgt)
- Step function (ft): IT → IT ➔ the function to be implemented
- Node function (FT): $ft^\omega = IT^\omega \rightarrow IT^\omega$

Abstract Types:

- Abstract Segment (ASgt): k (≤k)
- Abstract Interface (AIT): tuple(ASgt)
- Abstract step function (Aft): AIT → AIT

Bounded Memory Property

A Connector C from node N to N'



The FIFO associated with C is bounded if:

#produced tokens = #consumed tokens (on the long run)

If we know the **periods** of N and N': p_N, $p_{N'}$

Then, the FIFO associated with C is bounded iff:

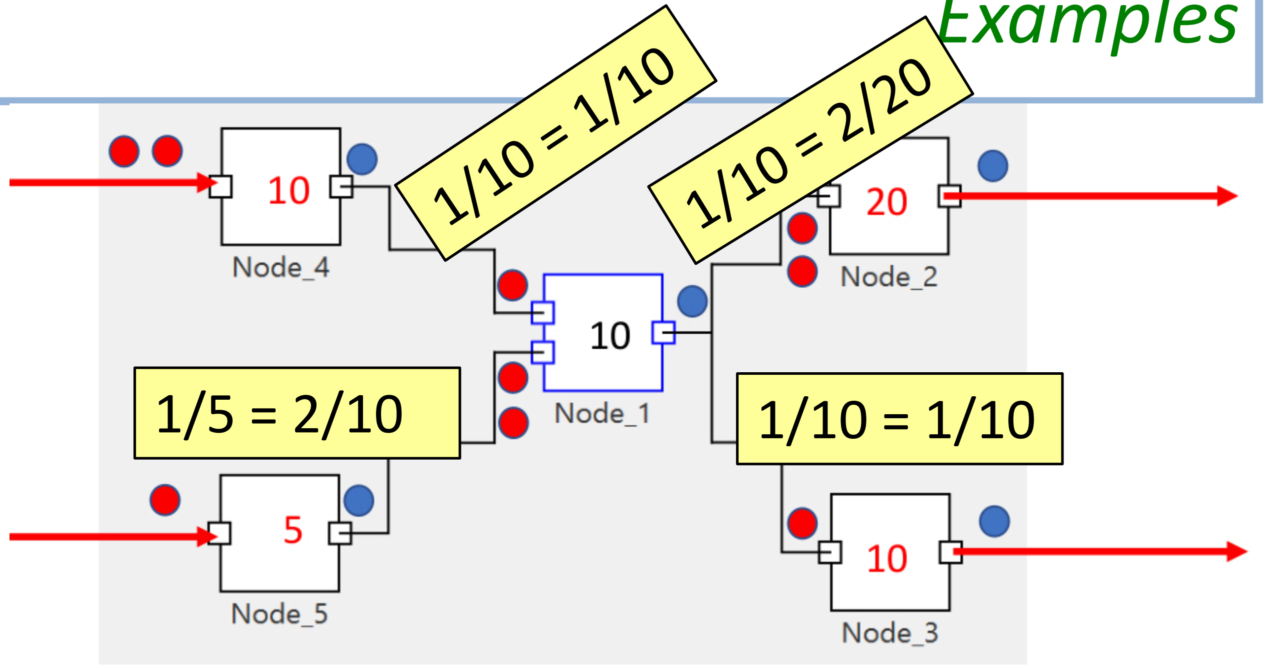
$$ASgt / p_N = ASgt / p_{N'}$$

That is : production rate = consumption rate

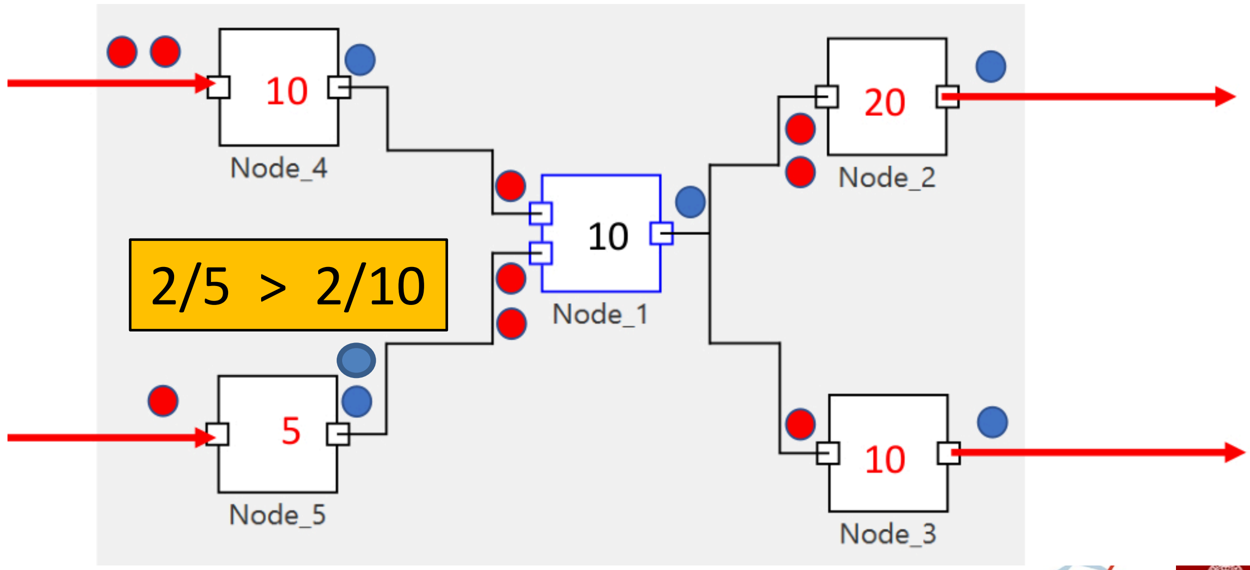
Fact: A KPN is bounded if all its connectors are bounded

Examples

Bounded KPN

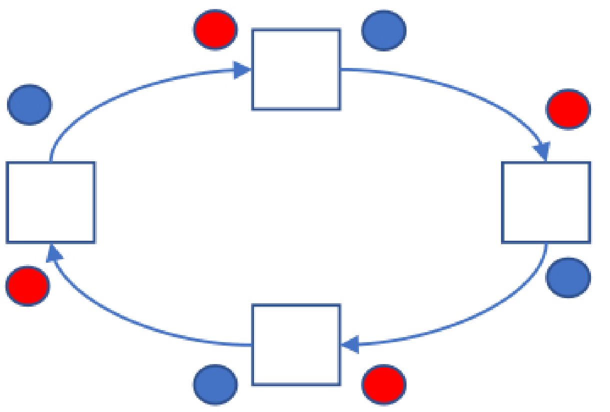


not Bounded KPN

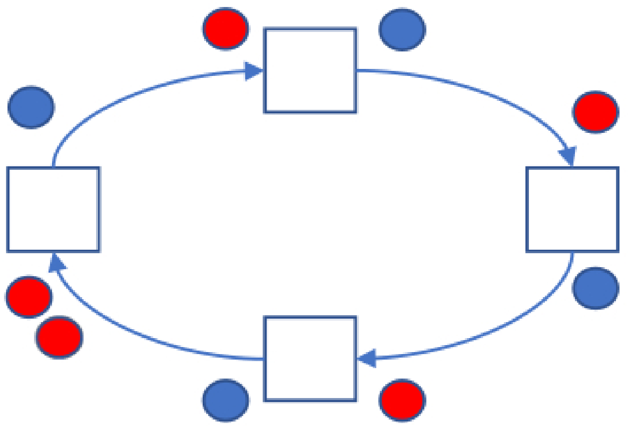


Do we need the periods ?

A live and bounded cycle: all have the same period (no node can consume more than its predecessor produces)



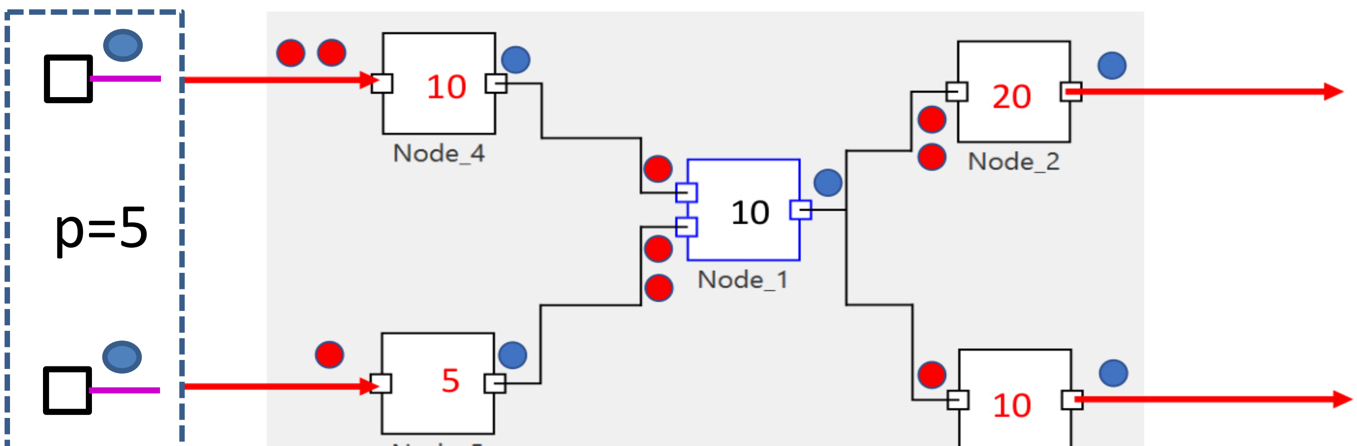
A deadlock cycle: for any period assignments different 0, the cycle asks to consume more than it produces



A more interesting setup

Idea: “Close” the system with an abstract interface representing the input rates for **some period p**:

➢ We can calculate the “effective periods” of all nodes (if a solution exist).



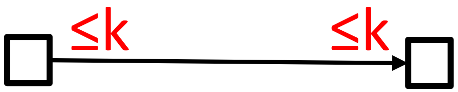
Interface type

Fact: we can efficiently compute the interface type of any composition

Can we go further ?

Fact: this "simple case" covers the "clock correctness" analysis of synchronous programs (Lustre)

Consider Connector C of type



A **deterministic protocol** allows dynamically adapting read-write strategies without impacting other components/connections

Fact: A type correct KPN is bounded memory and deadlock free.

… and if the execution time of all the programs implementing the step functions can be bounded, the e2e-delay of all system functions is also be bounded

Important lesson

General form of the step function

1. Read strategy (deterministic)
2. Local computation
3. Write strategy (deterministic)

Type

Any other abstraction of read/write strategies can be used for type analysis … as long as it can be handled by some tool

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