Analysis and Optimization of Distributed Real-Time Embedded Systems

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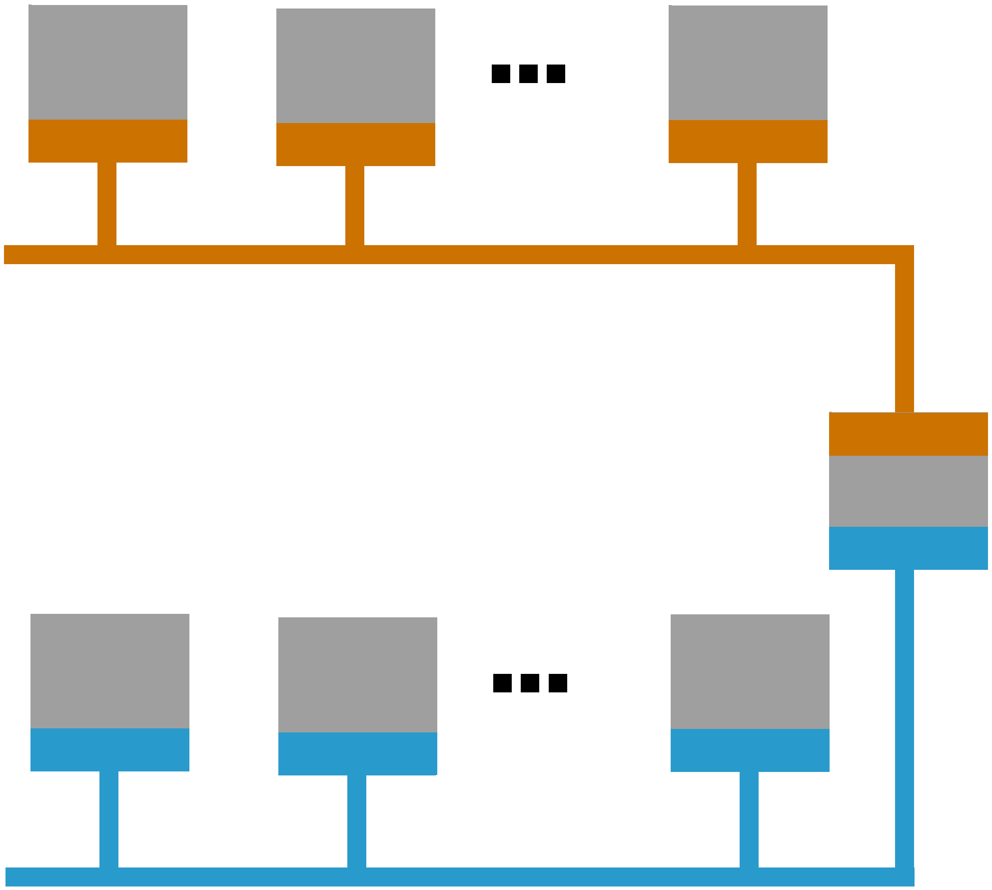
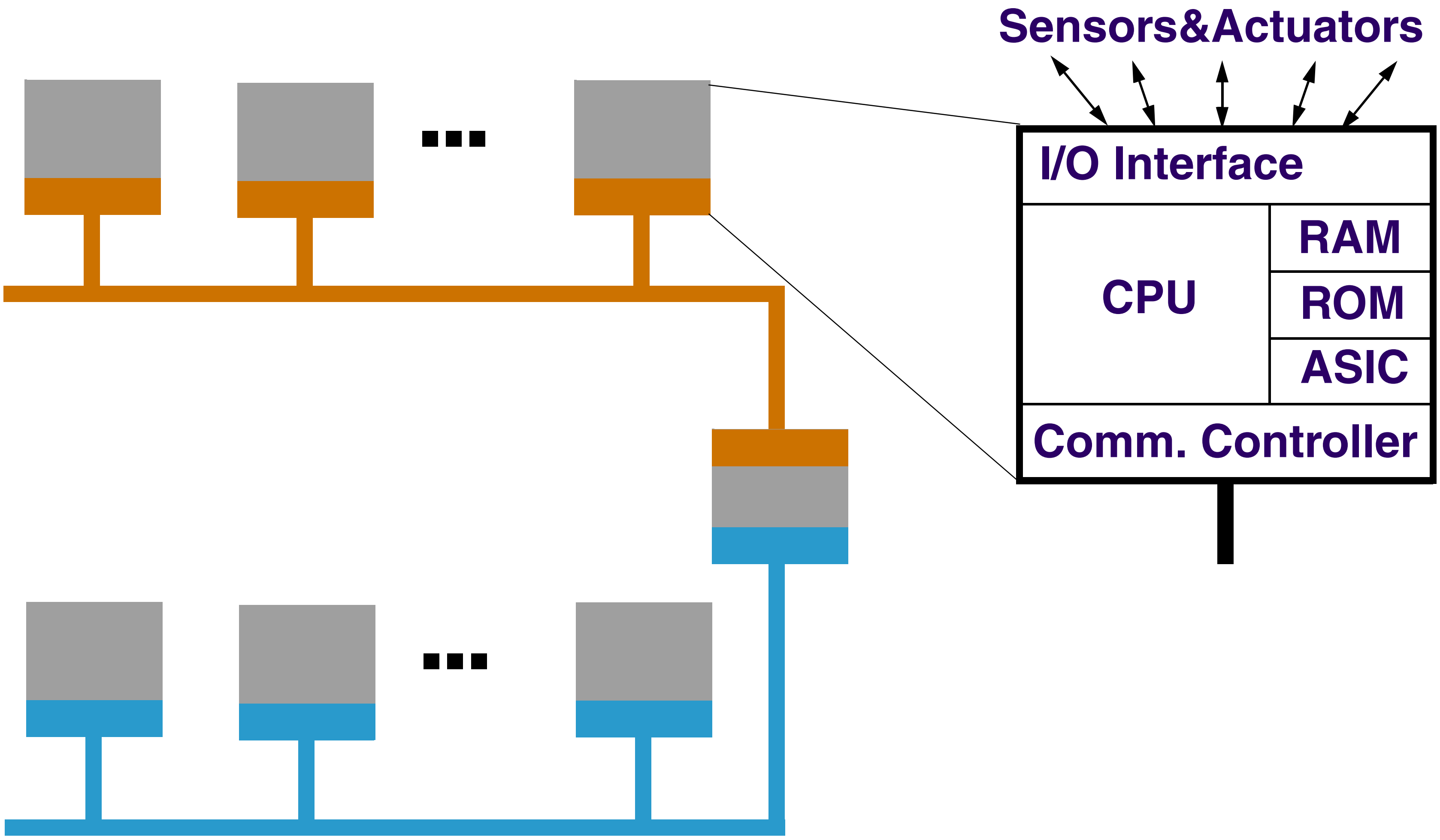
Outline

- Distributed Embedded Systems
- System-level Design Flow
- Application Model
- Distributed Hard Real-Time Systems
  - Heterogeneous Distributed Systems
  - Static and Dynamic Communication
  - Analysis & Optimization
  - Fault Tolerance
- Distributed Soft Real-Time Systems
  - Analysis Approaches and Optimization
  - Optimization

Distributed Embedded Systems



Distributed Embedded Systems



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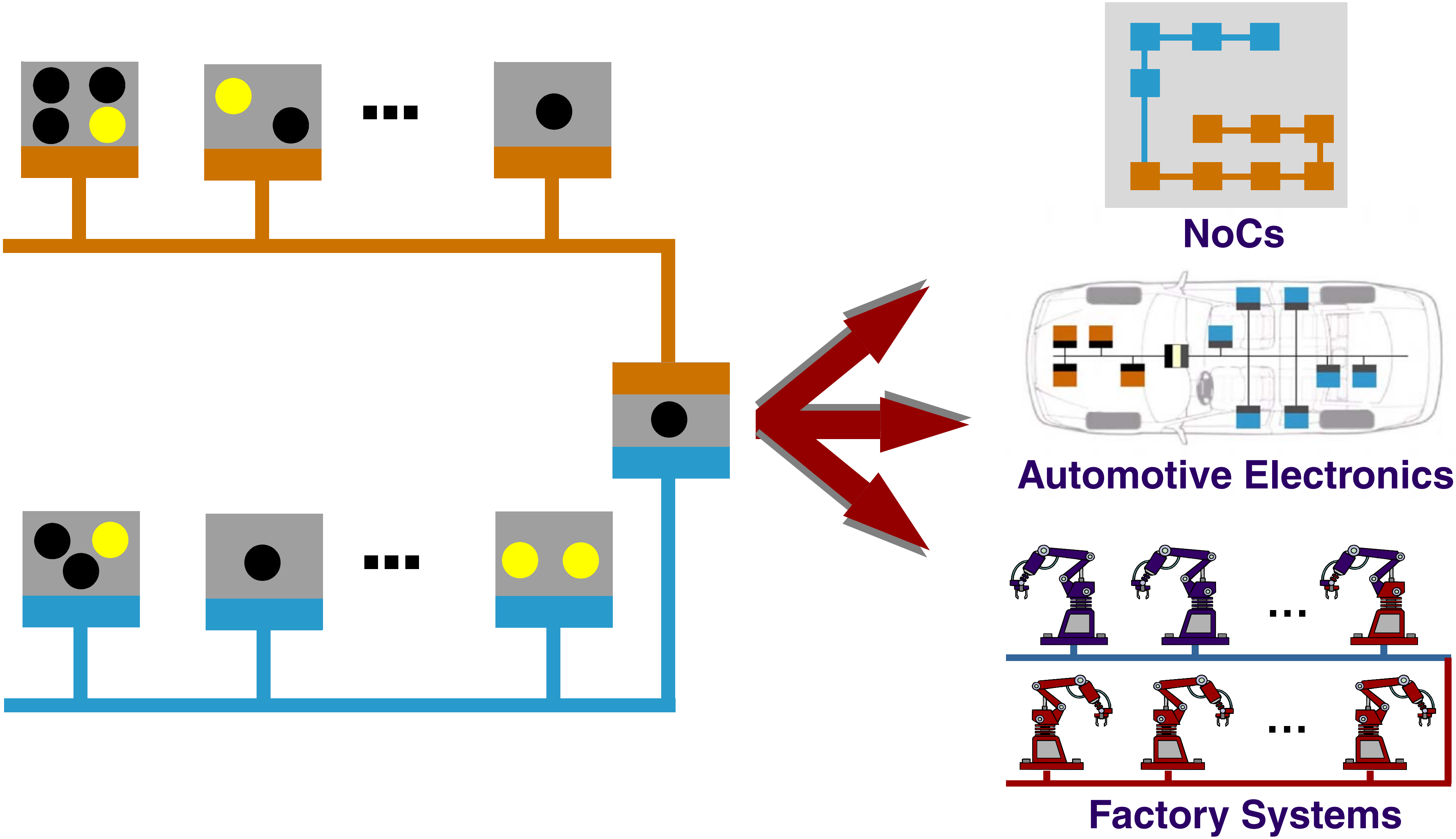
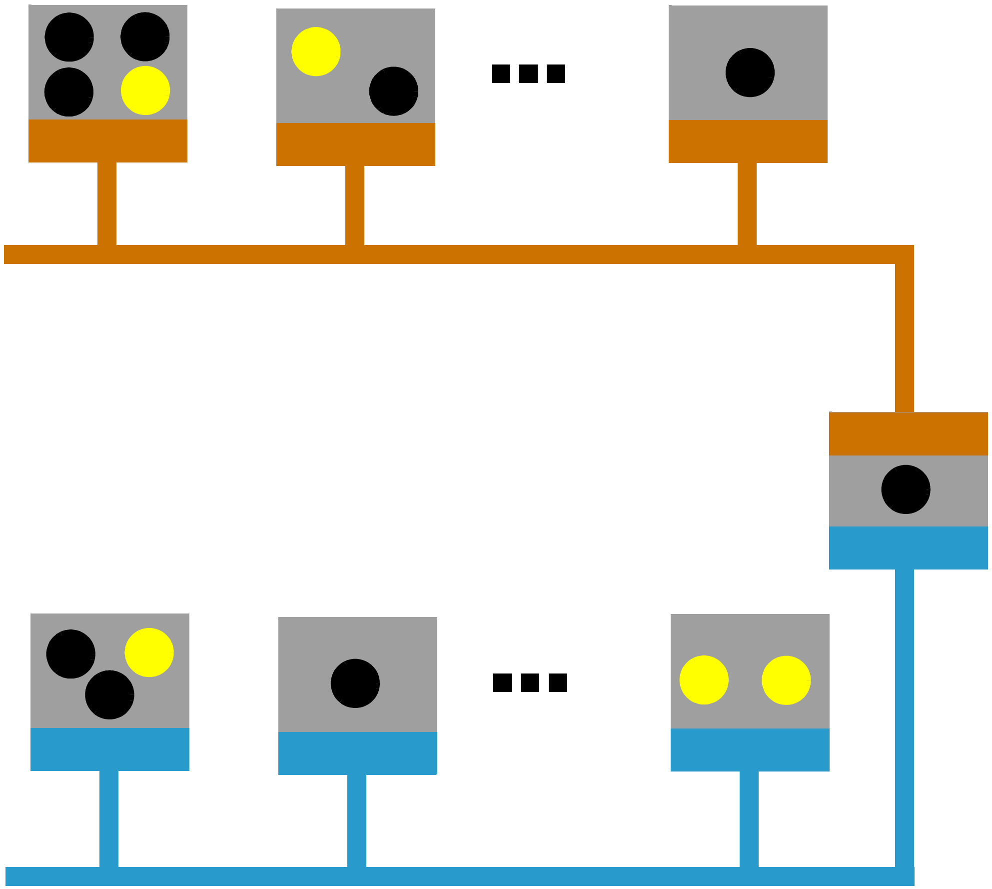


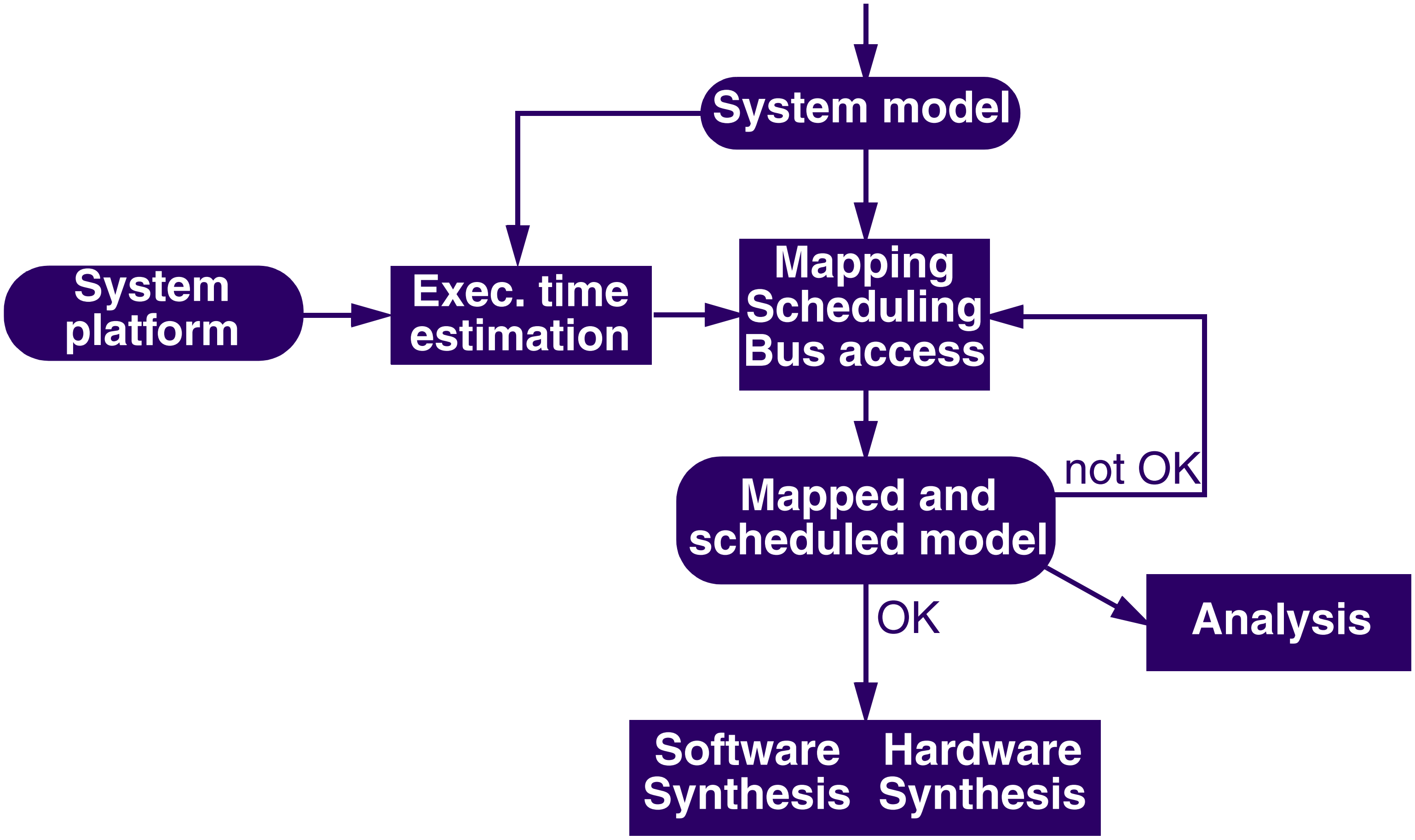
Distributed Embedded Systems



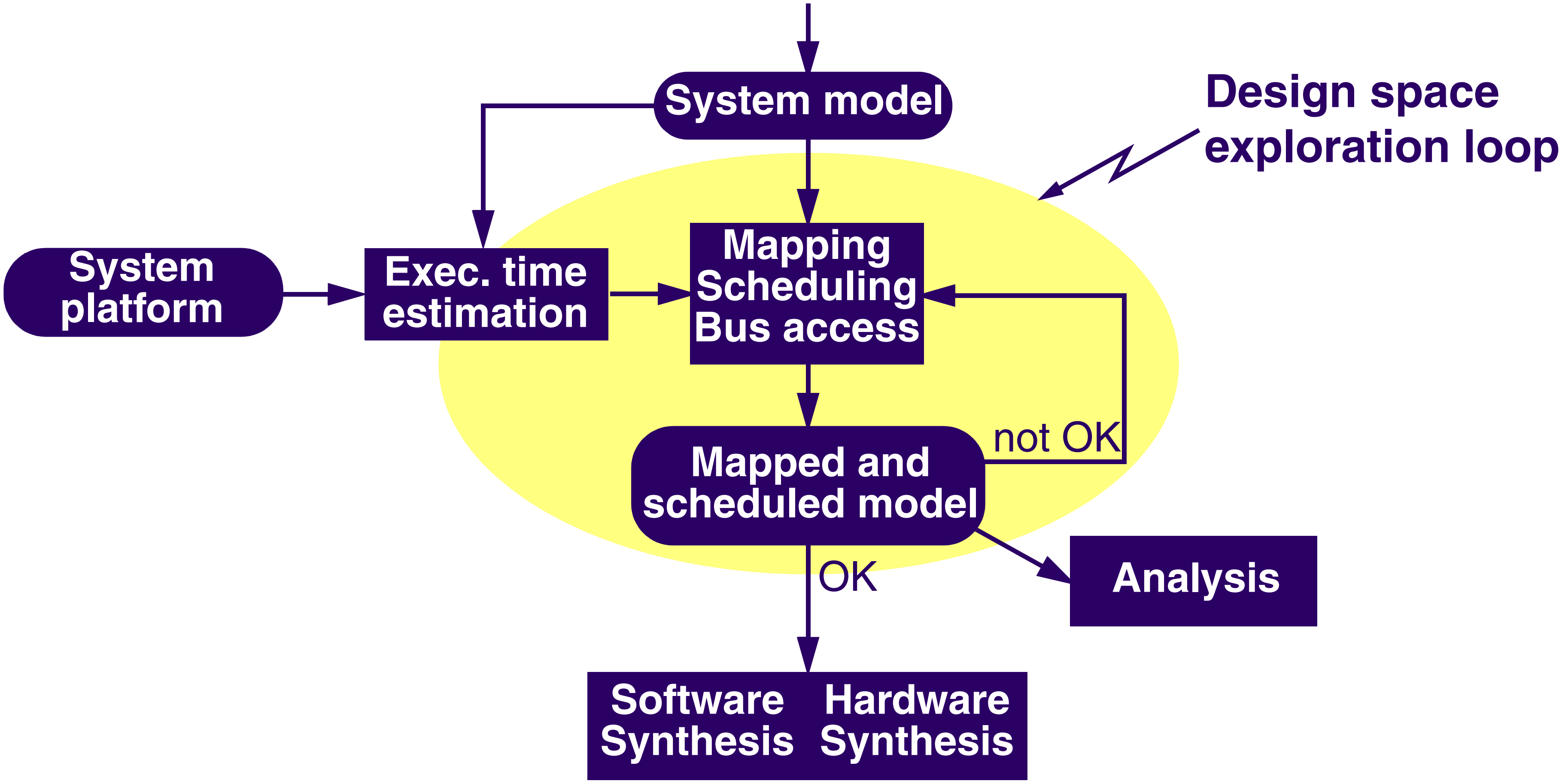
Why?

- **Physical constraints**
  - **Operation close to sensor;**
- **Modularity constraints**
- **Safety Constraints**
- **Performance**

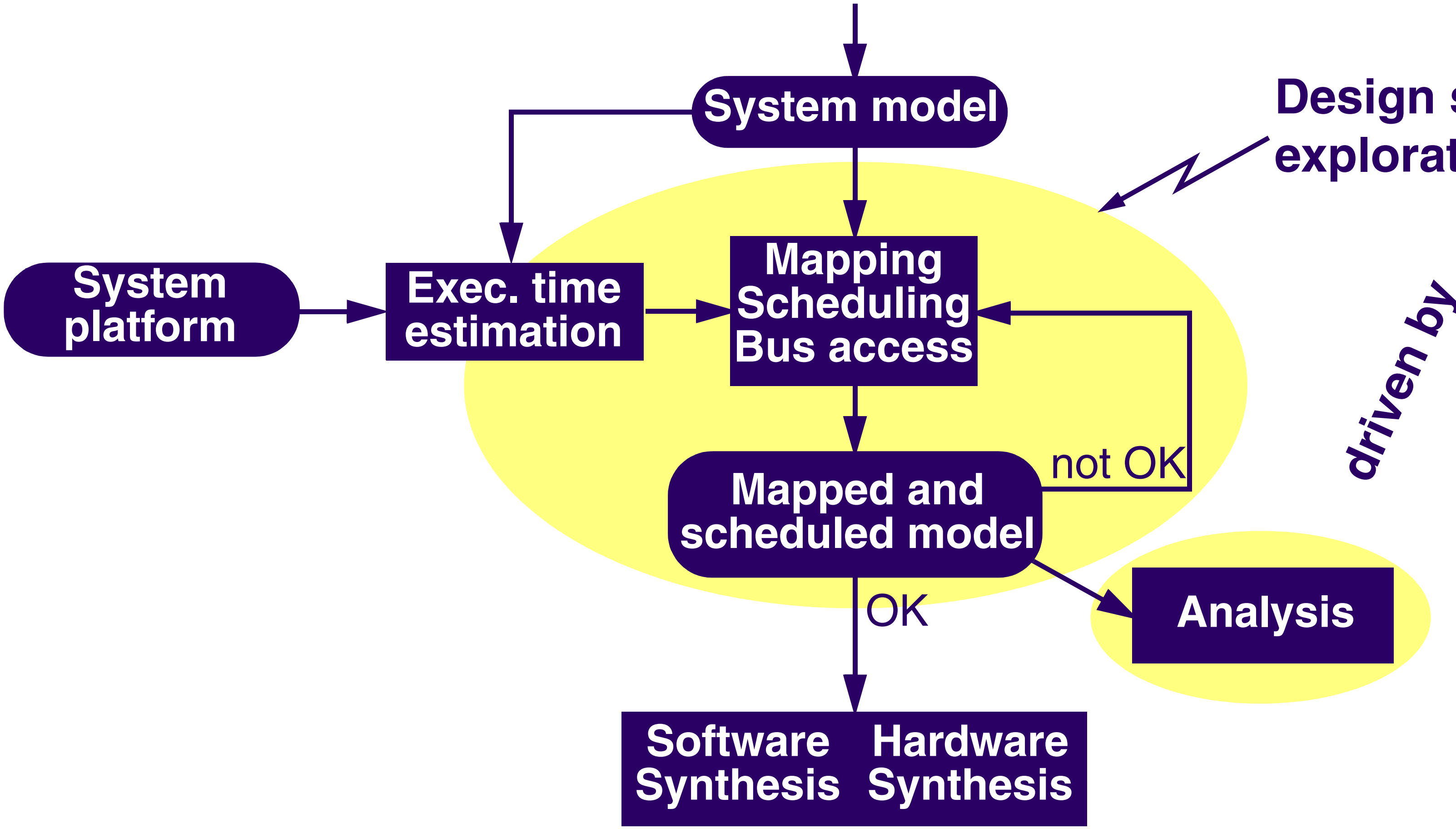
System Level Design Flow



System Level Design Flow

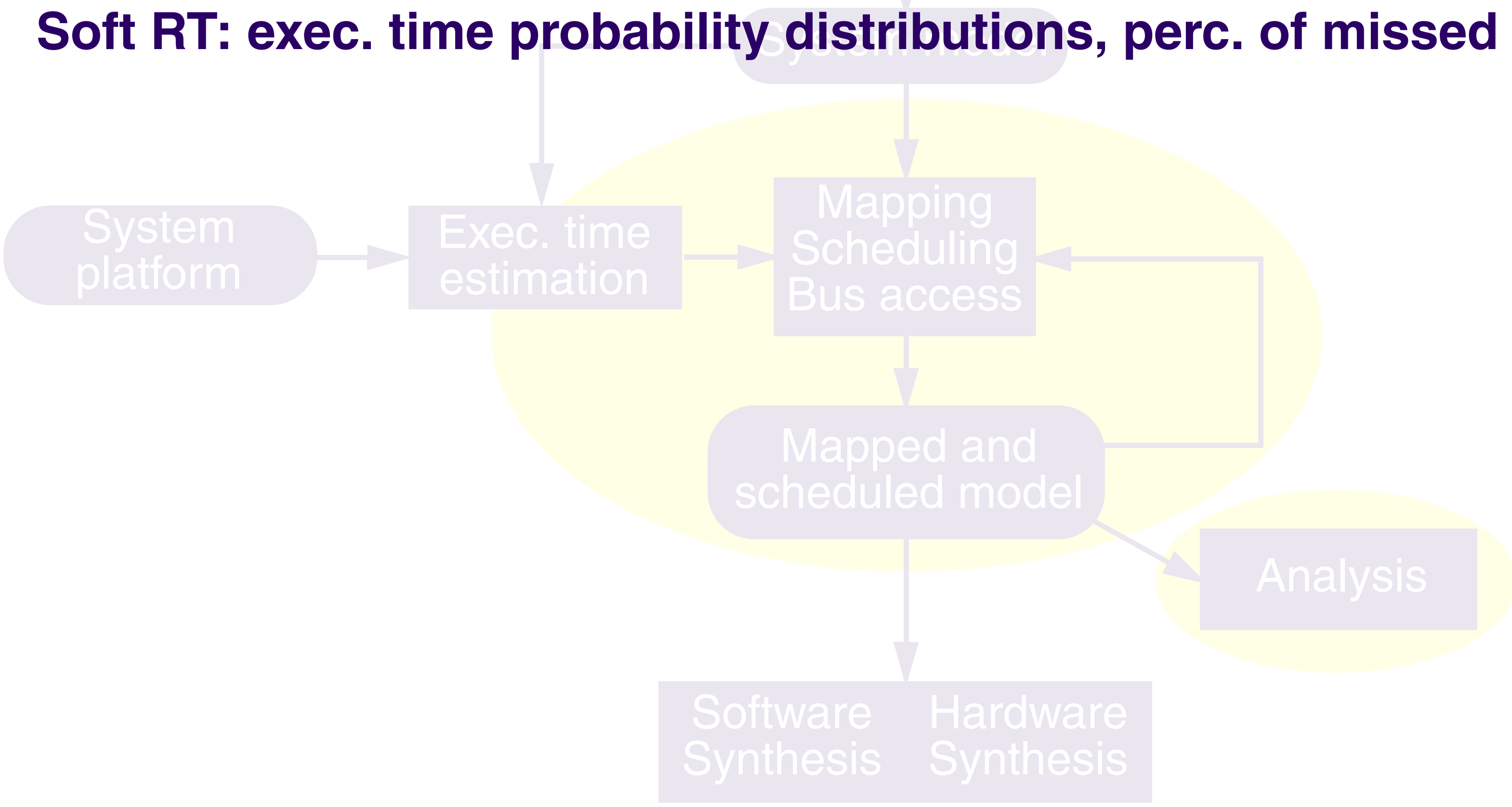


System Level Design Flow



System Level Design Flow

- **Category of applications:**
  - **Hard RT: WCET, hard deadlines to be satisfied**
  - **Soft RT: exec. time probability distributions, perc. of missed deadlines**



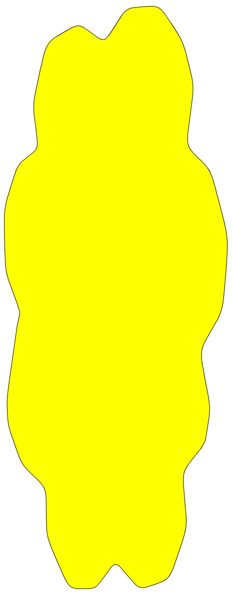
System Level Design Flow

- **Category of applications:**
  - **Hard RT: WCET, hard deadlines to be satisfied**
  - **Soft RT: exec. time probability distributions, perc. of missed deadlines**
- **Constraints:**
  - **time constraints (hard, soft)**
  - **cost (amount of resources)**
  - **fault tolerance**

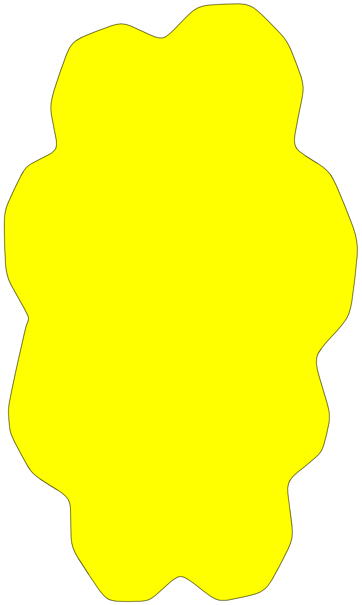
System Level Design Flow

- **Category of applications:**
  - **Hard RT: WCET, hard deadlines to be satisfied**
  - **Soft RT: exec. time probability distributions, perc. of missed deadlines**
- **Constraints:**
  - **time constraints (hard, soft)**
  - **cost (amount of resources)**
  - **fault tolerance**
- **Optimization problems:**
  - **schedule generation/priority assignment**
  - **task mapping**
  - **bus configuration**
  - **scheduling policy assignment**
  - **fault tolerance policy assignment**

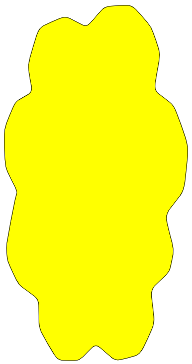
- **An application is modelled as a set of task graphs:**



Γ_1
Period: $T_{\Gamma 1}$
Deadline: $D_{\Gamma 1}$



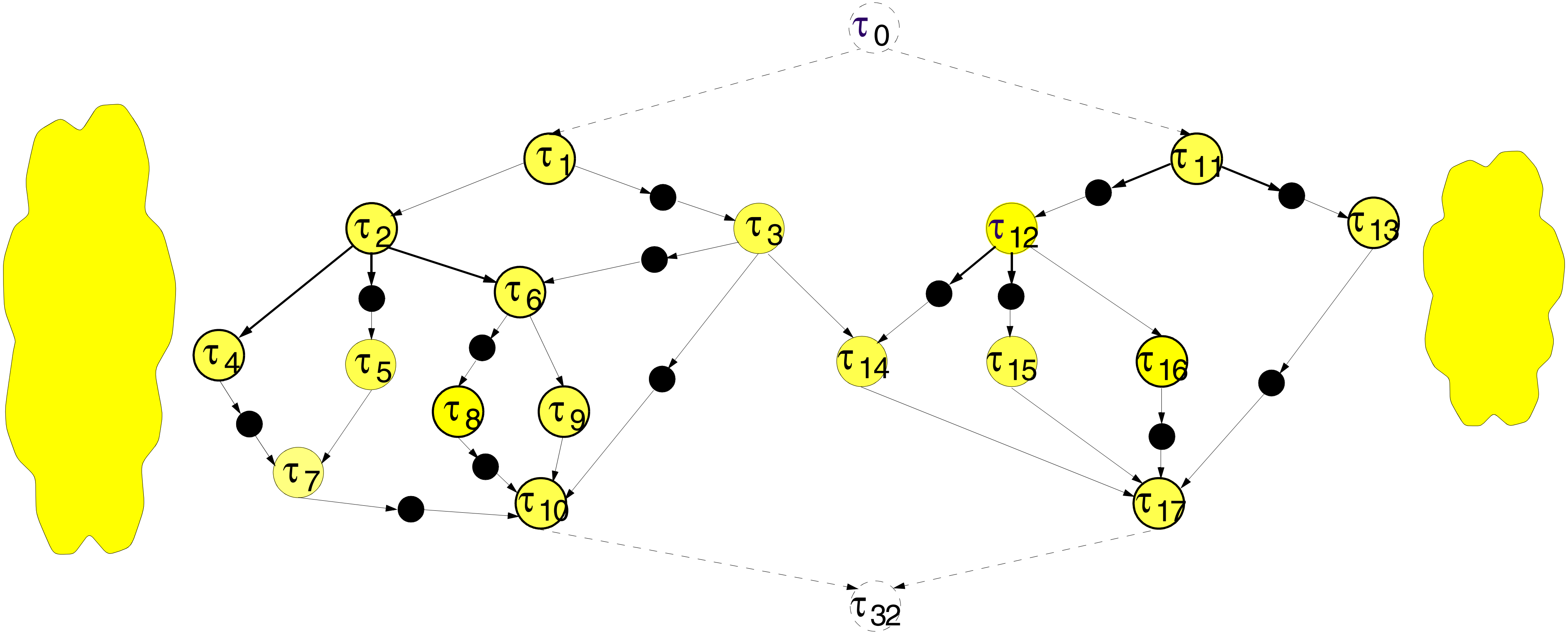
Γ_2
Period: $T_{\Gamma 2}$
Deadline: $D_{\Gamma 2}$



Γ_3
Period: $T_{\Gamma 3}$
Deadline: $D_{\Gamma 3}$

Application Model

☞ **An application is modelled as a set of task graphs:**



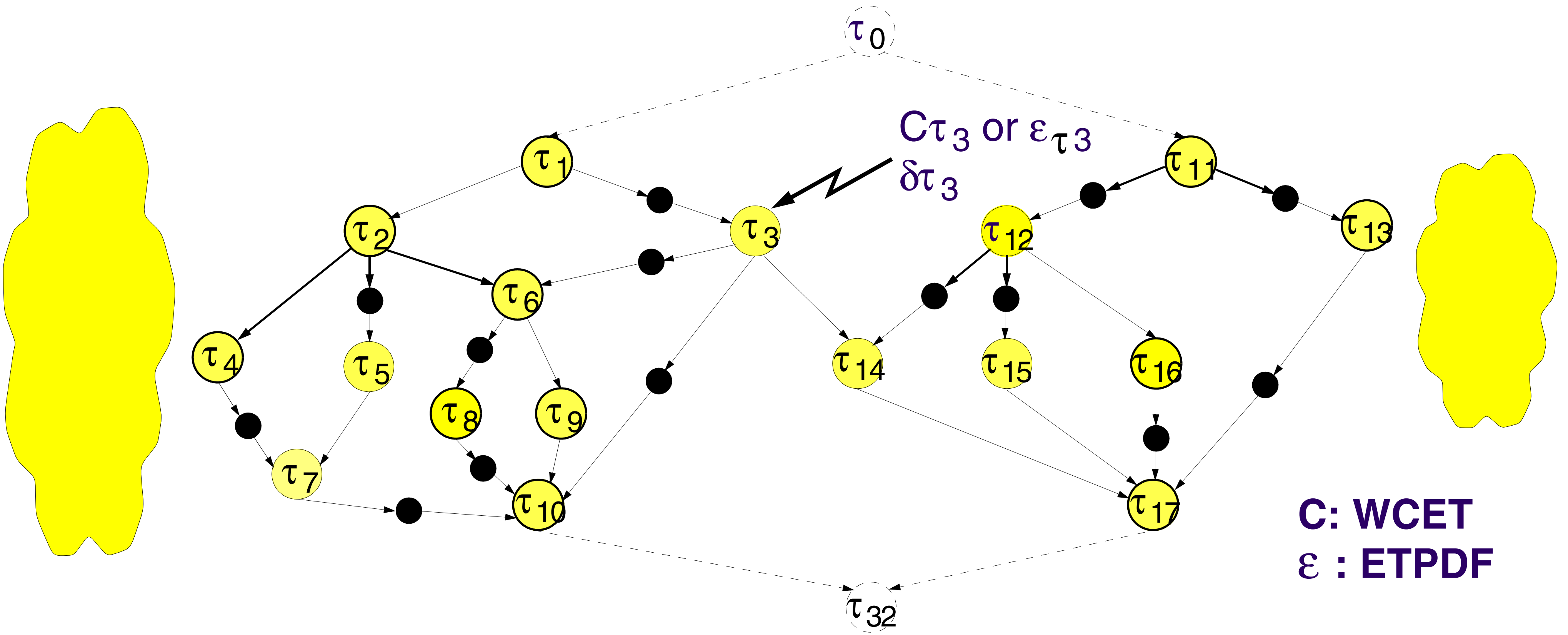
Γ_1
Period: $T_{\Gamma 1}$
Deadline: $D_{\Gamma 1}$

Γ_2
Period: $T_{\Gamma 2}$
Deadline: $D_{\Gamma 2}$

Γ_3
Period: $T_{\Gamma 3}$
Deadline: $D_{\Gamma 3}$

Application Model

☞ **An application is modelled as a set of task graphs:**



C: WCET
ε : ETPDF

Γ_1
Period: $T_{\Gamma 1}$
Deadline: $D_{\Gamma 1}$

Γ_2
Period: $T_{\Gamma 2}$
Deadline: $D_{\Gamma 2}$

Γ_3
Period: $T_{\Gamma 3}$
Deadline: $D_{\Gamma 3}$

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Distributed Hard Real-Time Systems

- **Given:**
  - **WCET and BCET of each task**
  - **Dimension of messages**
  - **Deadlines for tasks/task graphs**

☞ **All deadlines have to be satisfied!**

Distributed Hard Real-Time Systems

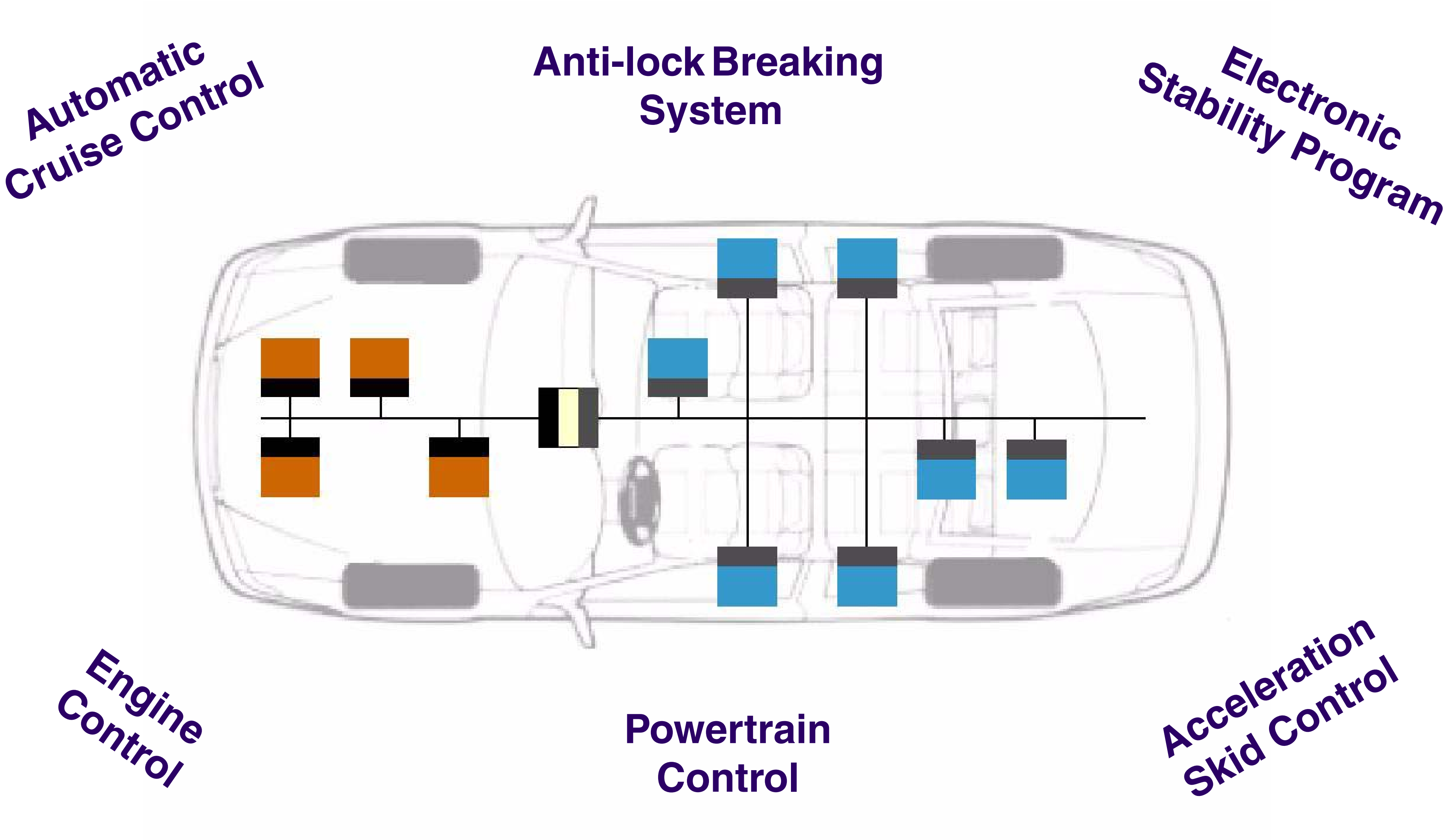
- Given:
  - WCET and BCET of each task
  - Dimension of messages
  - Deadlines for tasks/task graphs

☞ All deadlines have to be satisfied!

- Particular issues taken into consideration
  - Heterogeneous nature of the system
  - Various communication protocols

☞ Try to satisfy constraints at low cost!

Application Area



Heterogeneous Distributed Embedded Systems

- **RT Design Approach**

- **Network Protocol**

Heterogeneous Distributed Embedded Systems

- **RT Design Approach**
  - Time triggered
  - Event triggered

- **Network Protocol**

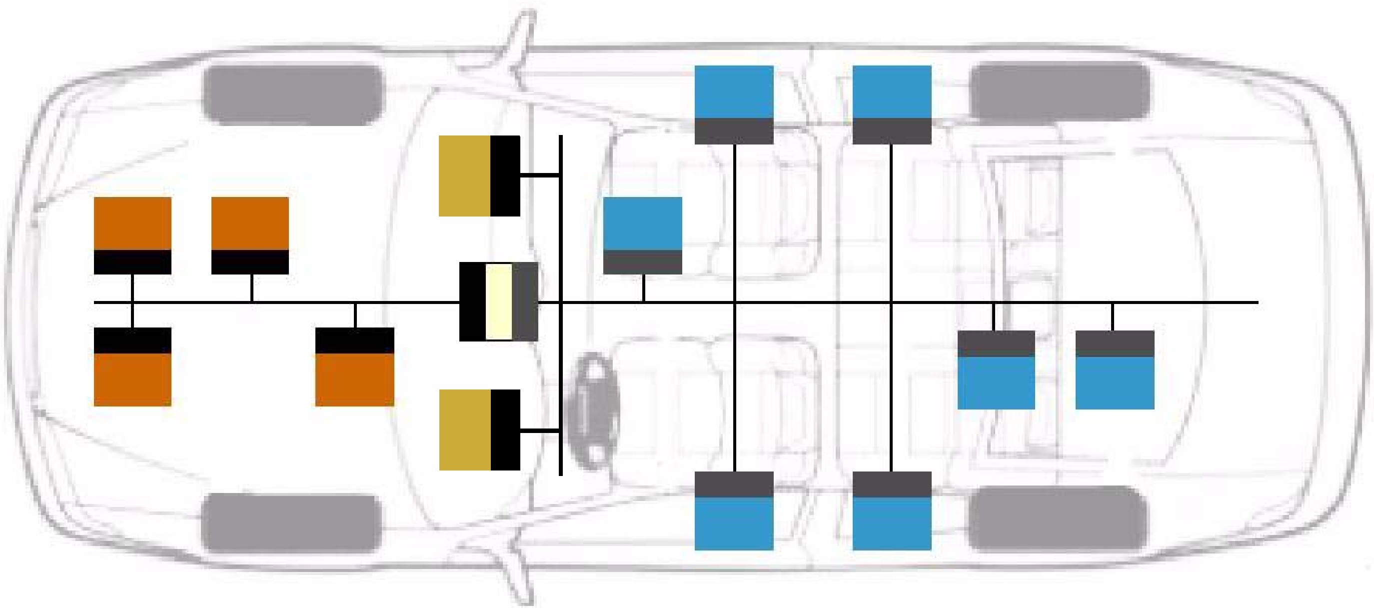
Heterogeneous Distributed Embedded Systems

- **RT Design Approach**
  - Time triggered
  - Event triggered

- **Network Protocol**
  - Static
  - Dynamic

Heterogeneous Distributed Embedded Systems

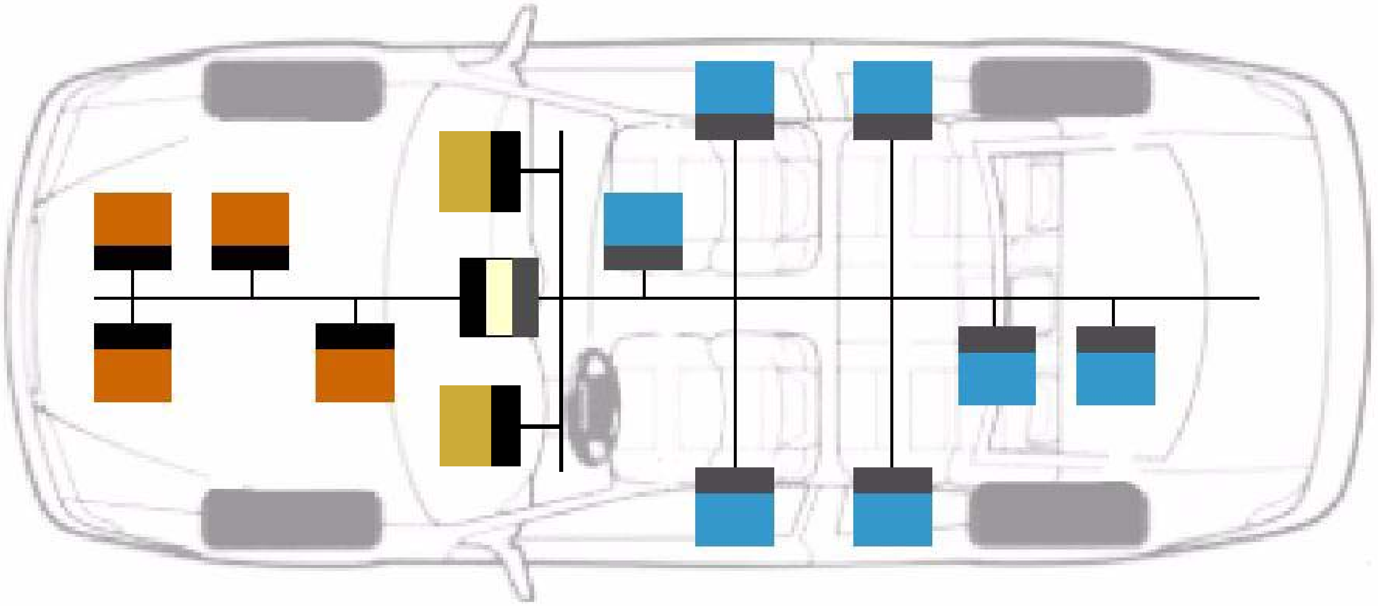
☞ **Heterogeneous Nature of Implemented Functions**



Heterogeneous Distributed Embedded Systems

Engine Control

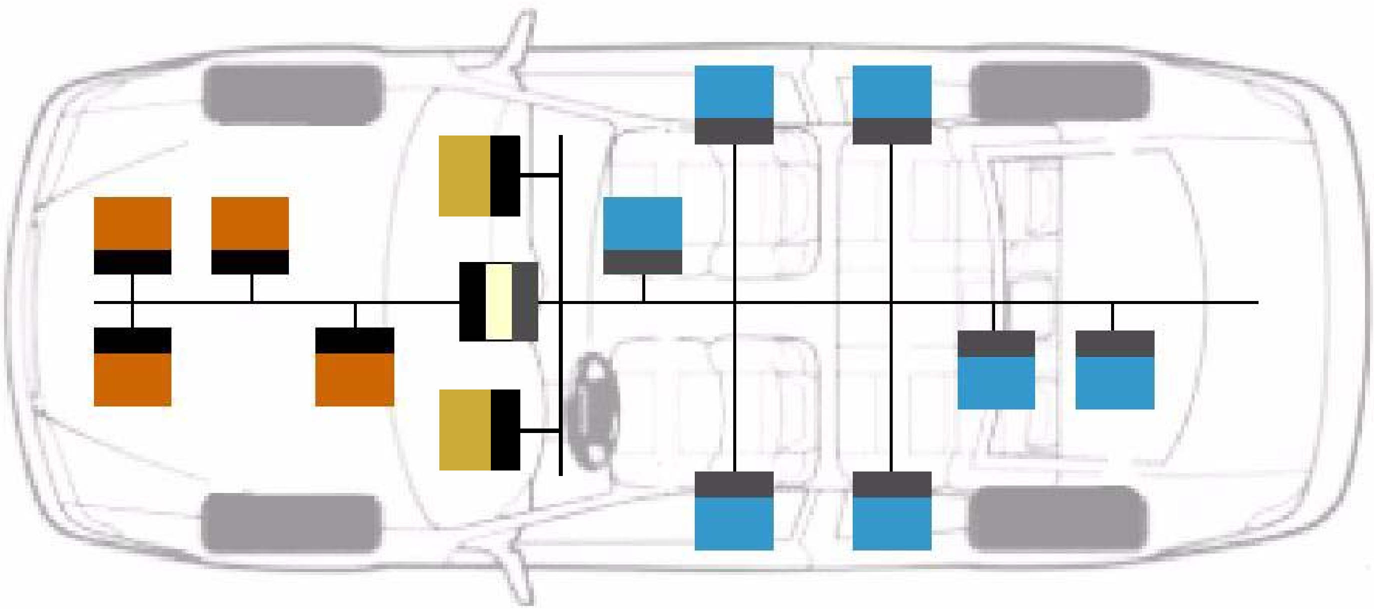
- **hard real-time**



Heterogeneous Distributed Embedded Systems

Engine Control
- hard real-time

Power Train (break-by-wire, ABS)
- hard real-time
- highly safety-critical



Heterogeneous Distributed Embedded Systems

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Power Train (break-by-wire, ABS)
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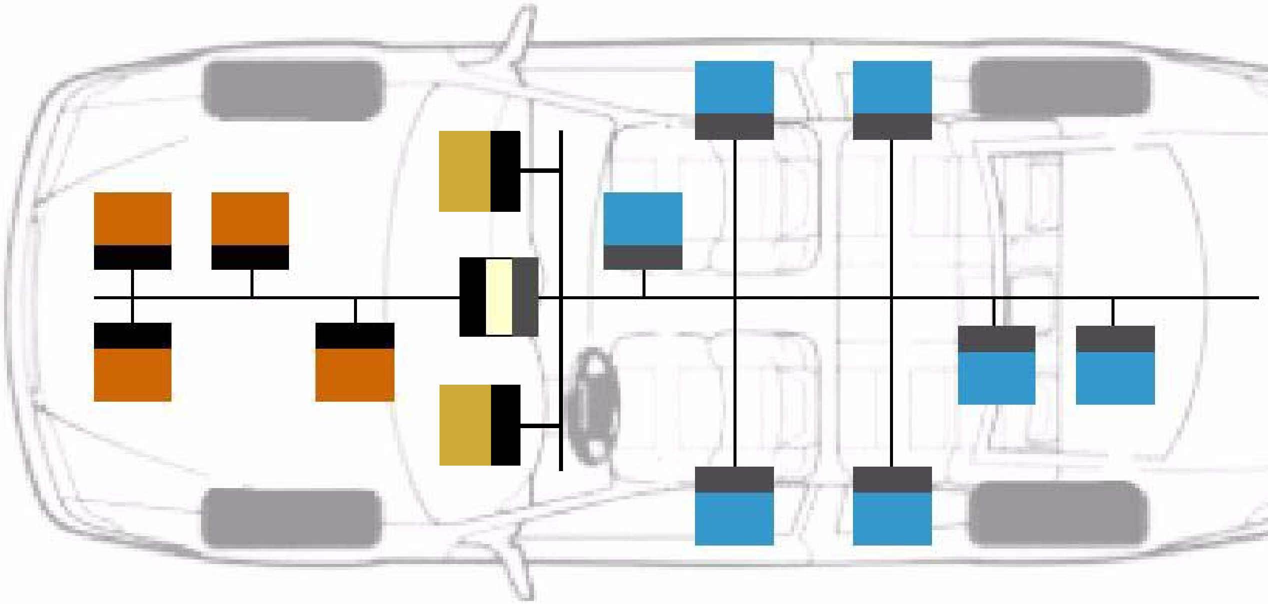
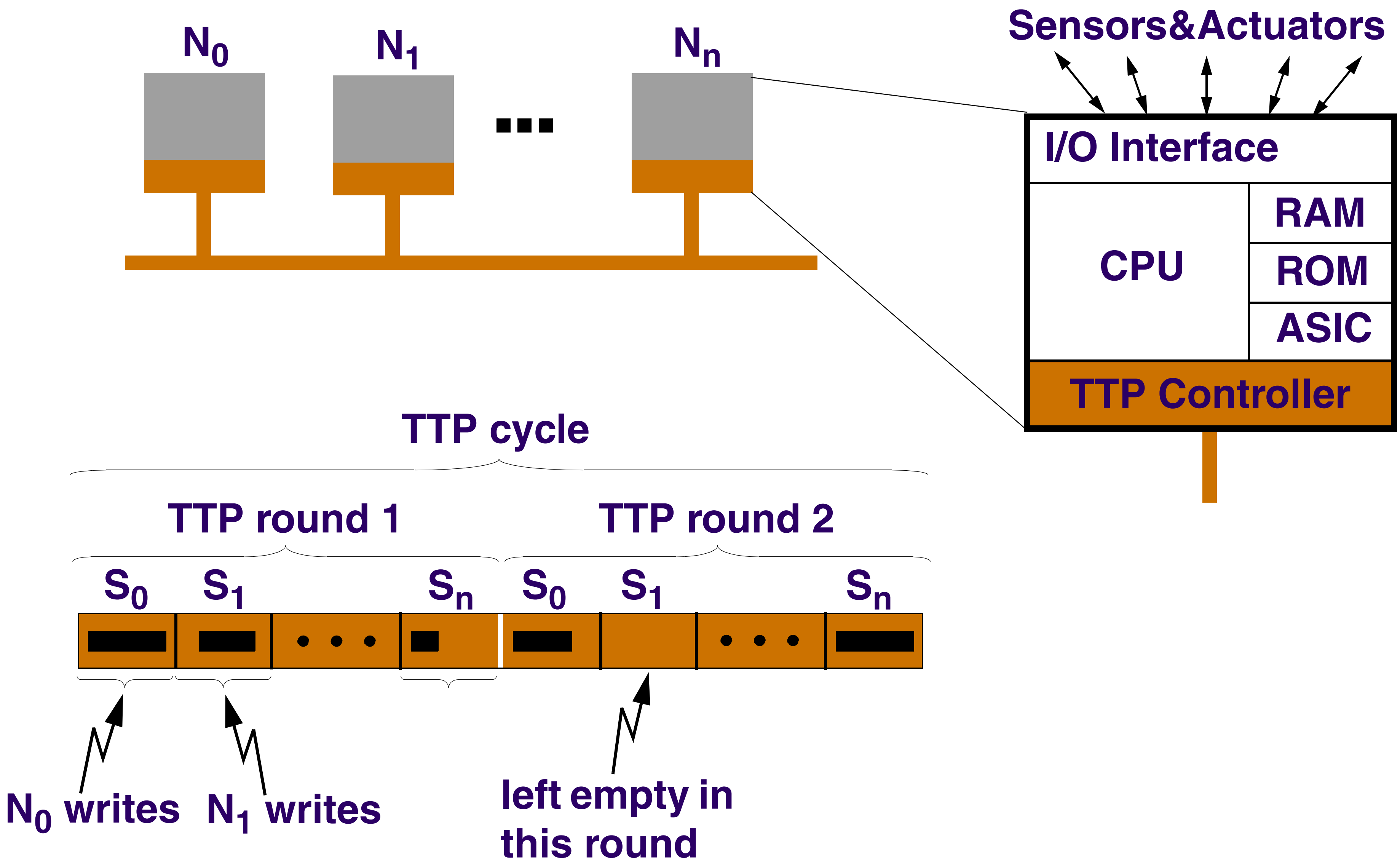
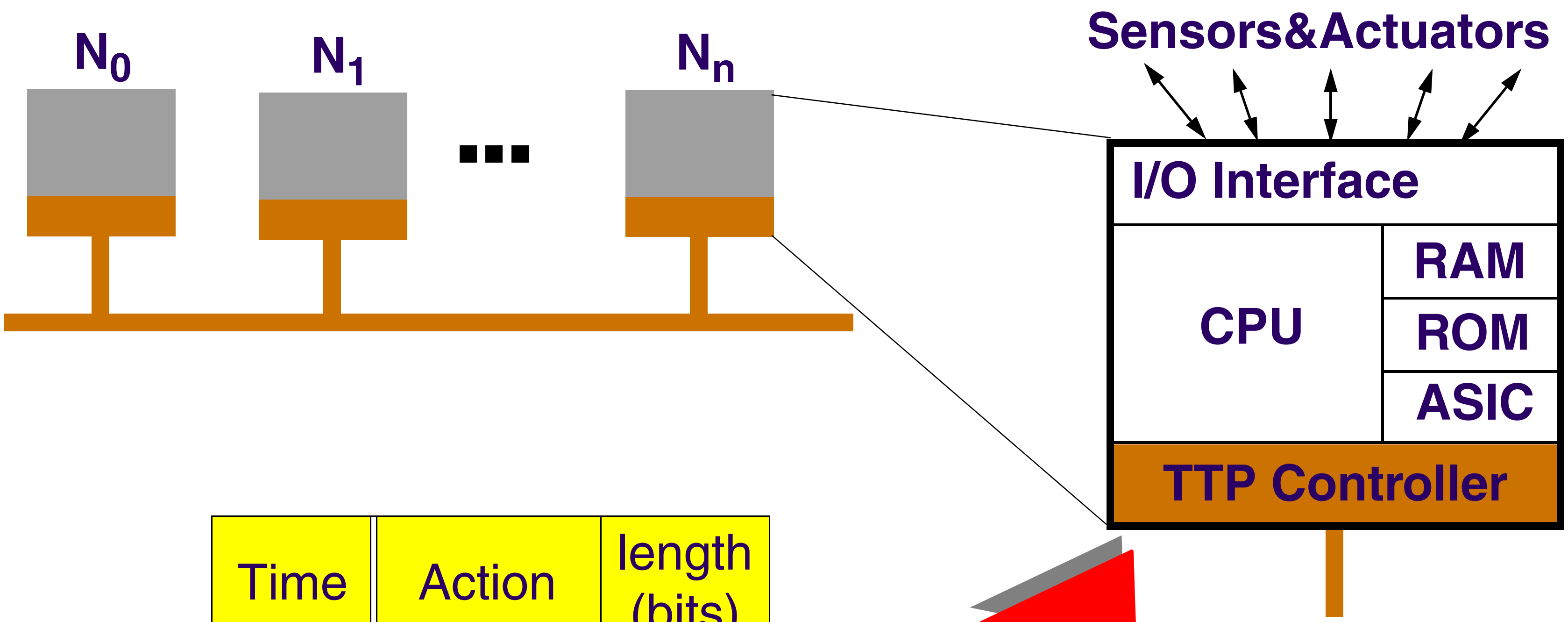


Air Conditioning
- soft real-time

Static Communication: TTP



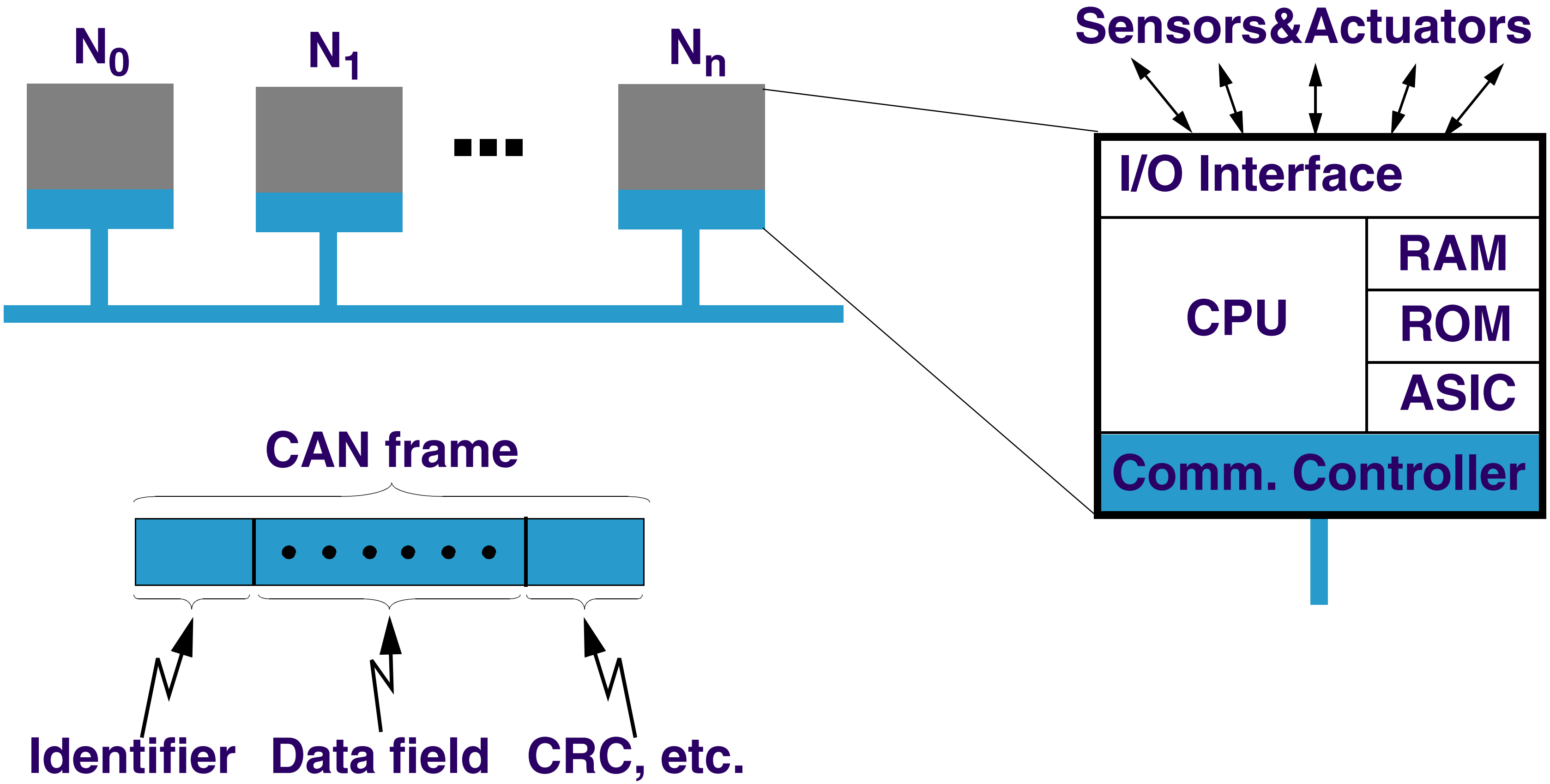
Static Communication: TTP



Over a TTP cycle

Time	Action	length (bits)
t_1	rd-frame	16
t_2	wr-frame	32
t_3	rd-frame	32
...	...	...
t_x	wr-frame	16

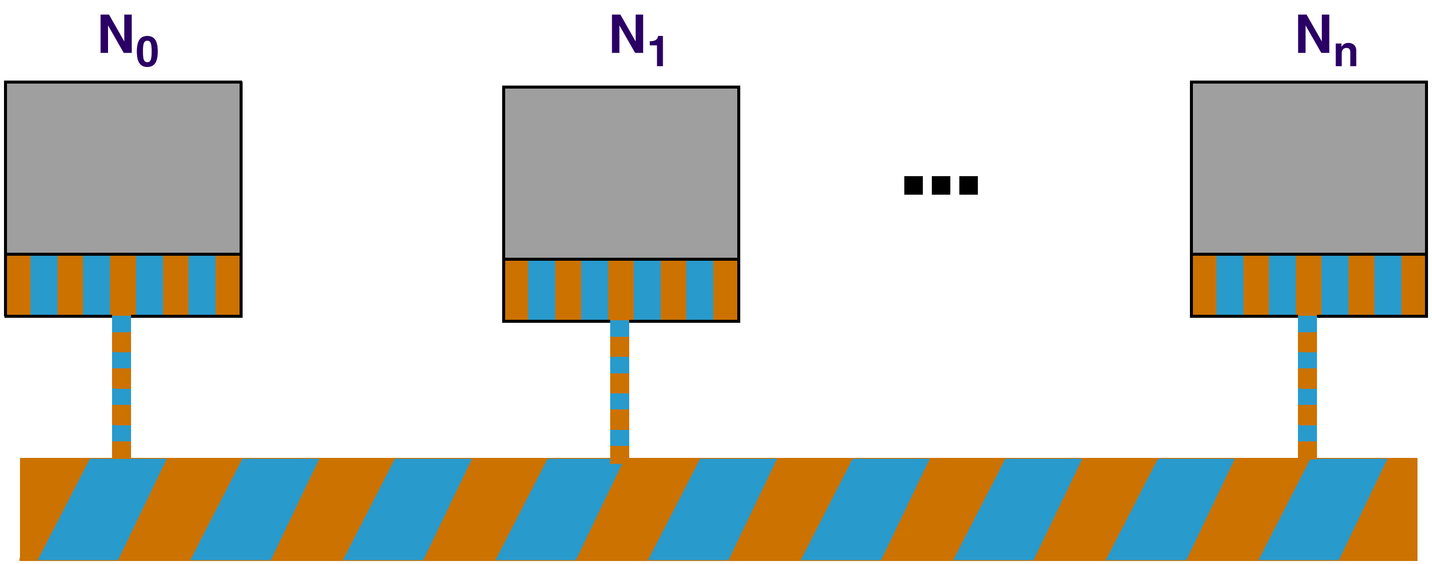
Dynamic Communication: CAN

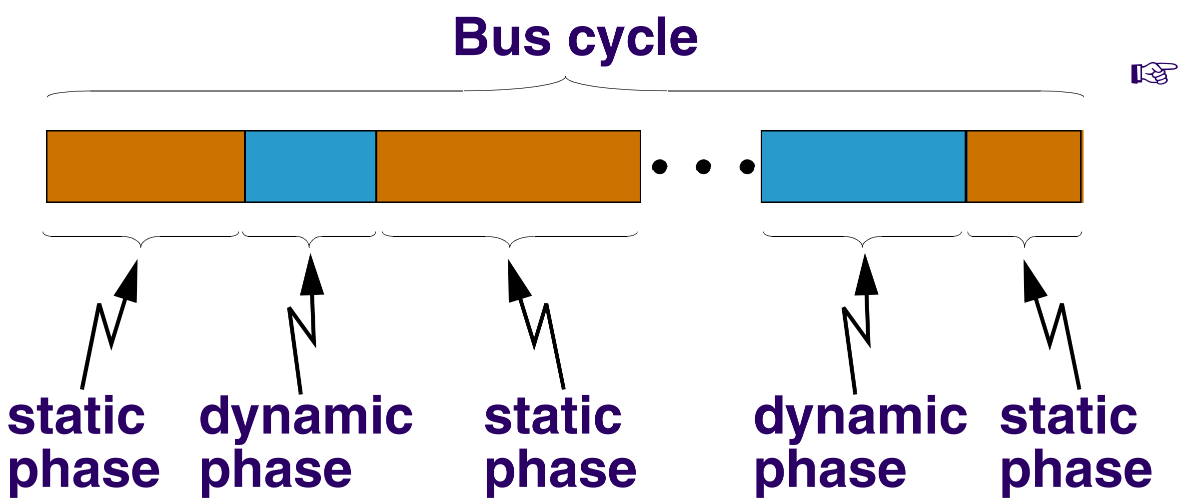


- **Priority bus with collision avoidance mechanism:**

  The node that transmits the highest priority frame wins the contention.

Mixed Communication: UCM

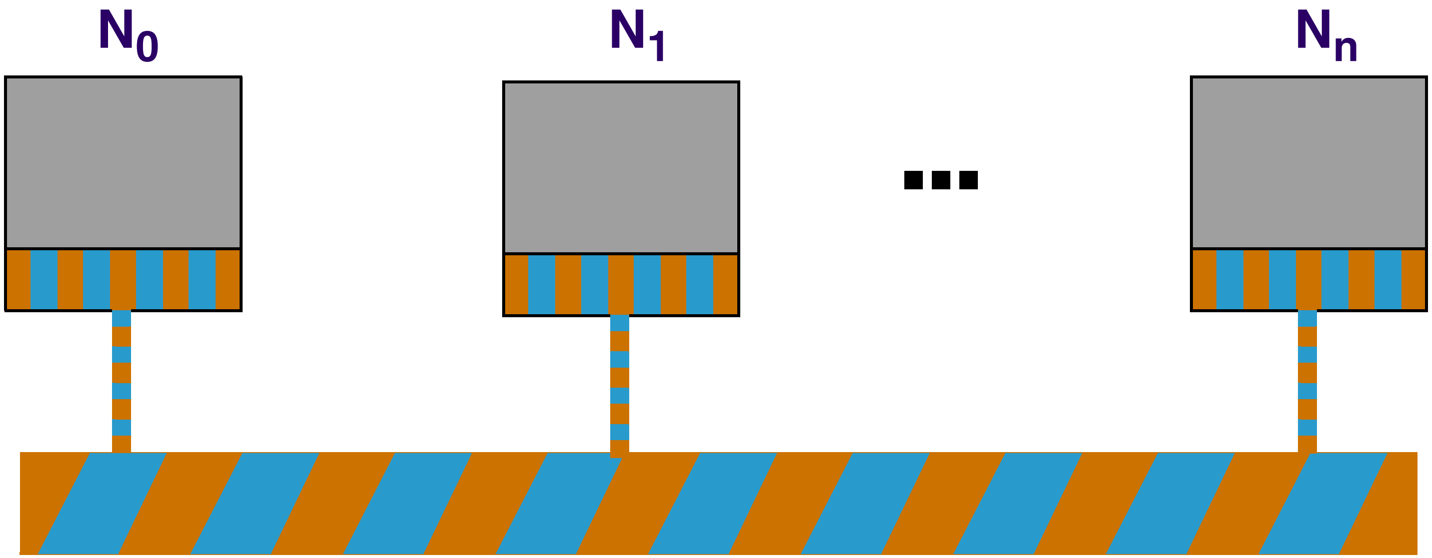


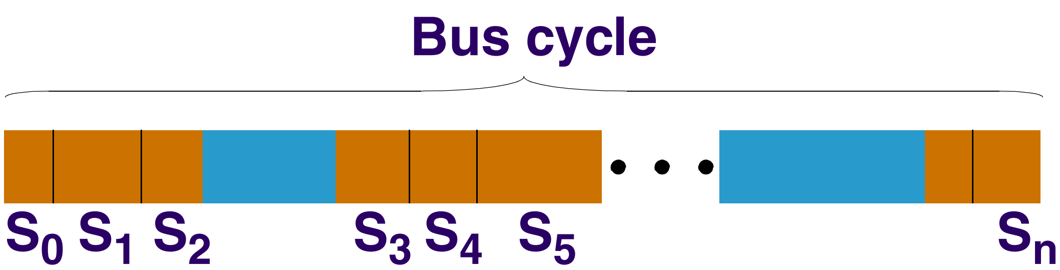


☞ **Universal Communication Model**

- **Static phase: TDMA**
- **Dynamic phase: CAN**

Mixed Communication: UCM

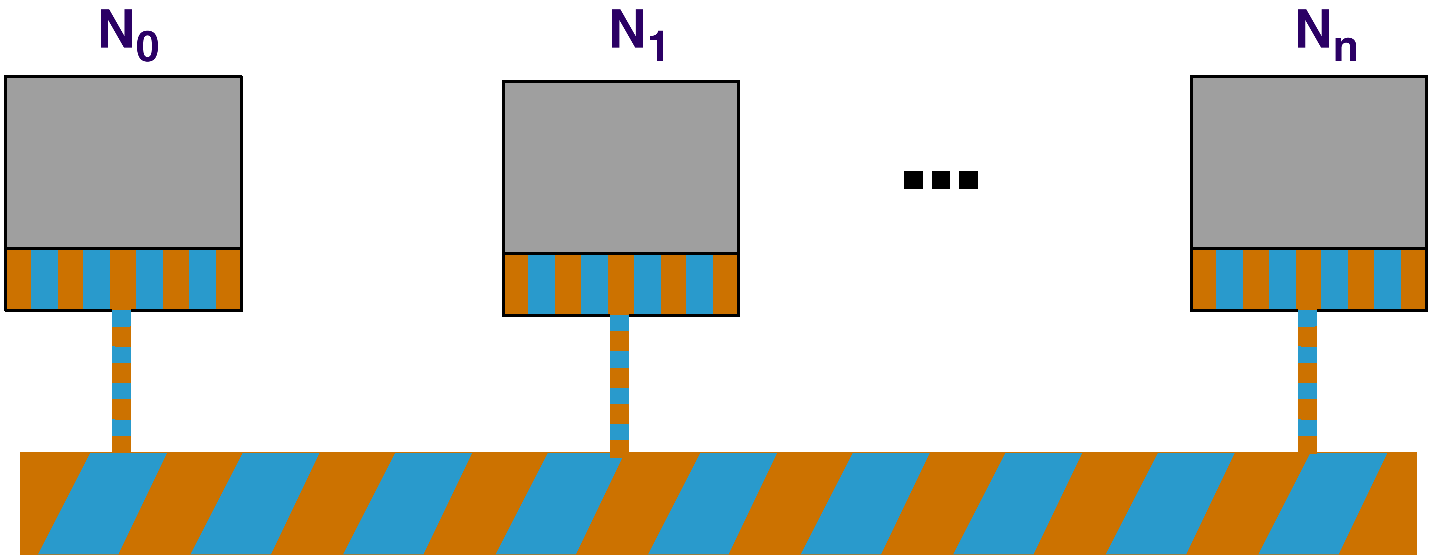


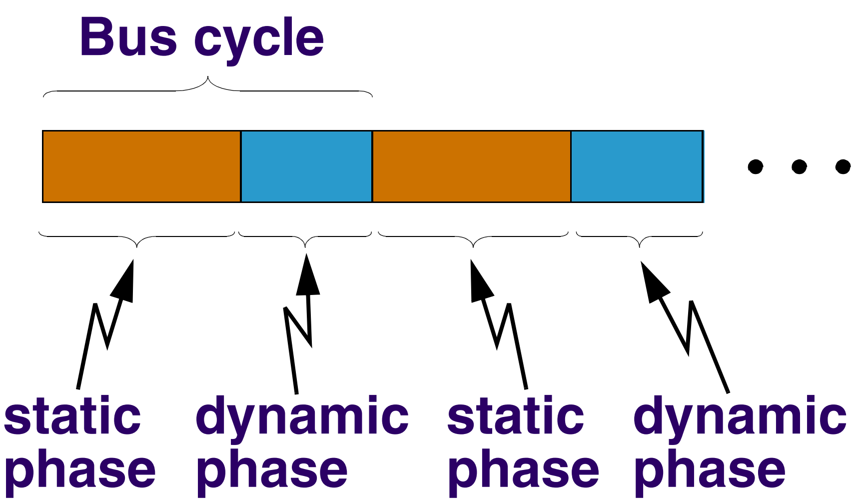


☞ **Universal Communication Model**

- **Static phase: TDMA**
- **Dynamic phase: CAN**

Mixed Communication: FlexRay

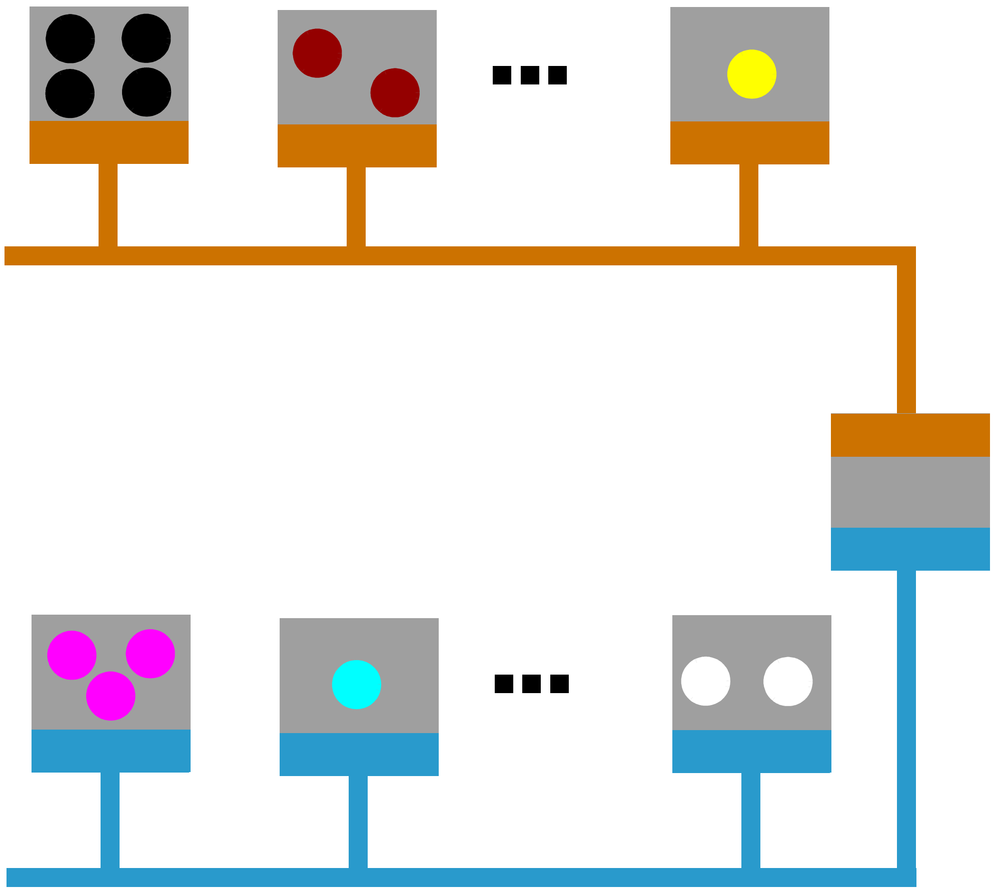




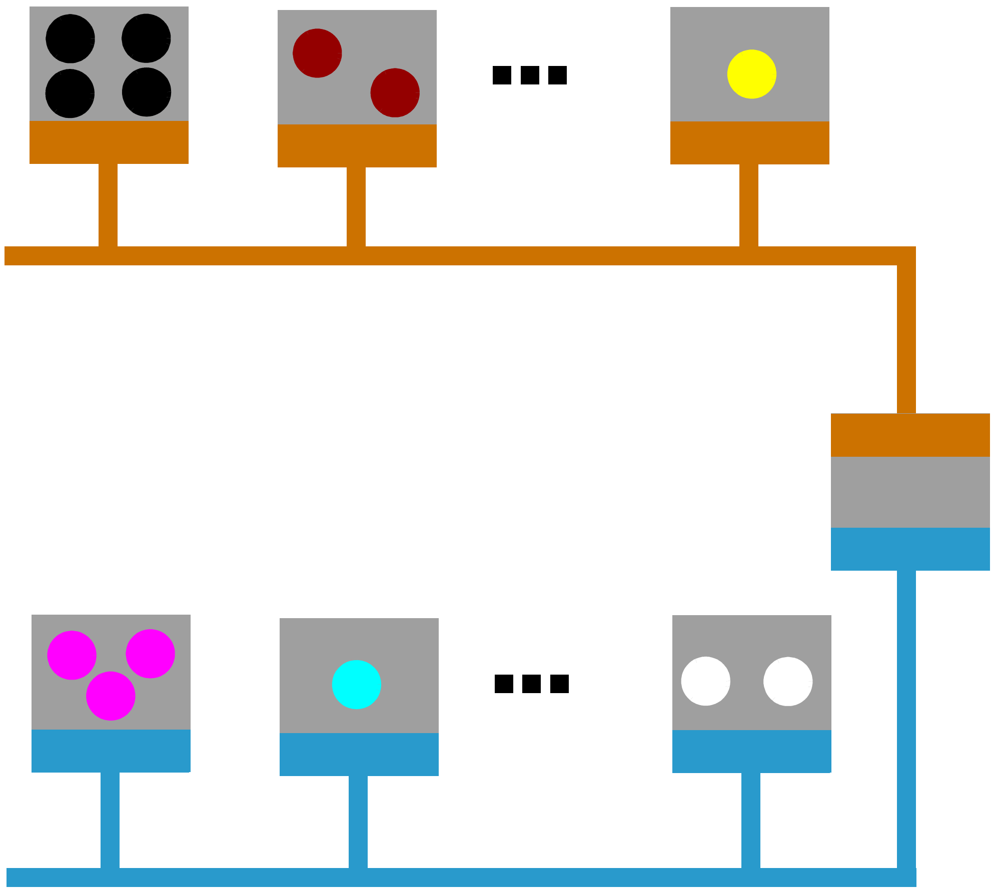
- FlexRay
  - Static phase: TDMA
  - Dynamic phase: Flexible TDMA

The Traditional Approach

One node ⟷ One function



The Traditional Approach



One node ⟷ One function

- Purchase node&function and integrate into system
- Sophistication grew quickly

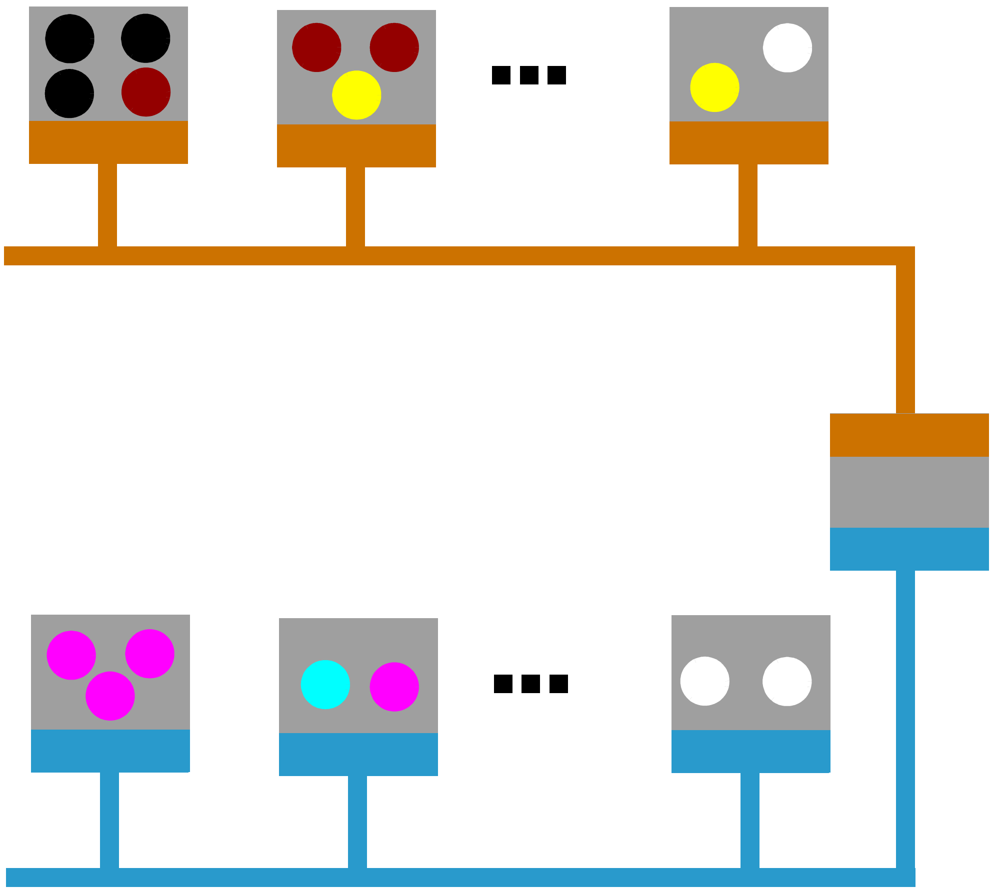
↓

More then 100 nodes

↓

Resources have to be used more efficiently

What Comes



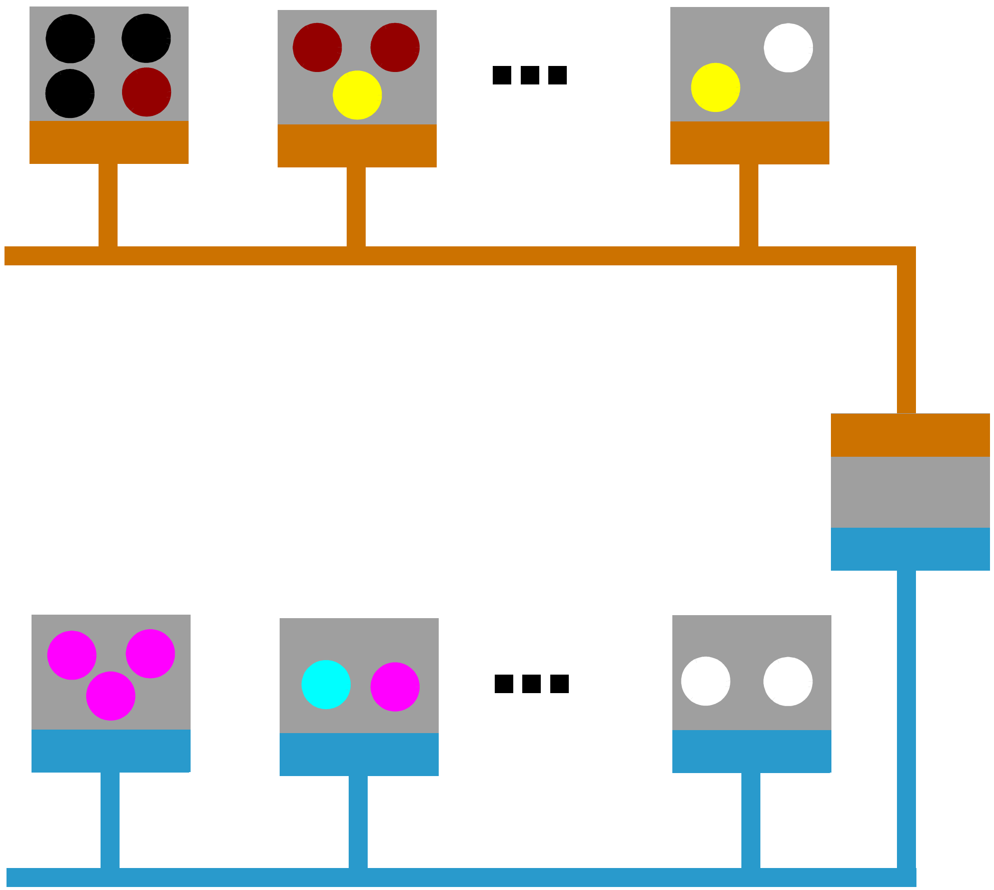
One node ⟷ Several functions

Several nodes ⟷ One function

Flexibility!

- Reduce cost
- Improve resource usage
- Function close to sensor

What Comes



One node ⟷ Several functions

Several nodes ⟷ One function

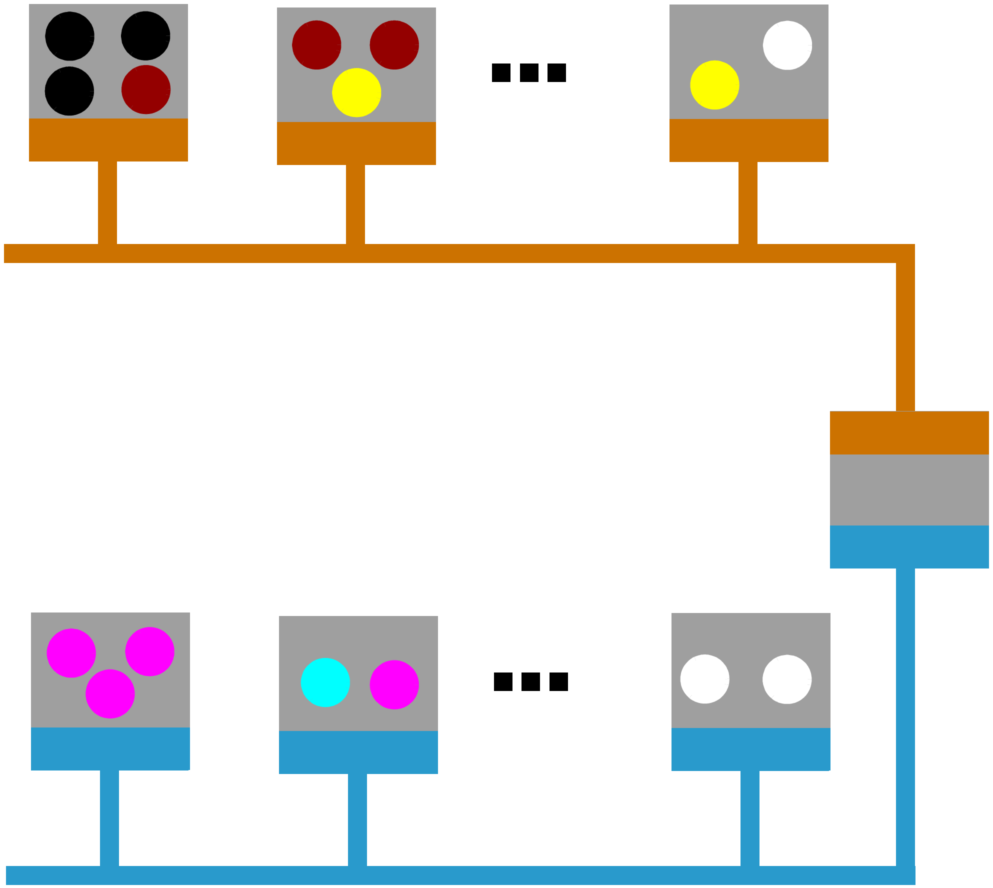
Flexibility!

- Reduce cost
- Improve resource usage
- Function close to sensor

☞ Needed:

- Middleware software
- New analysis
- New system optimization

What Comes

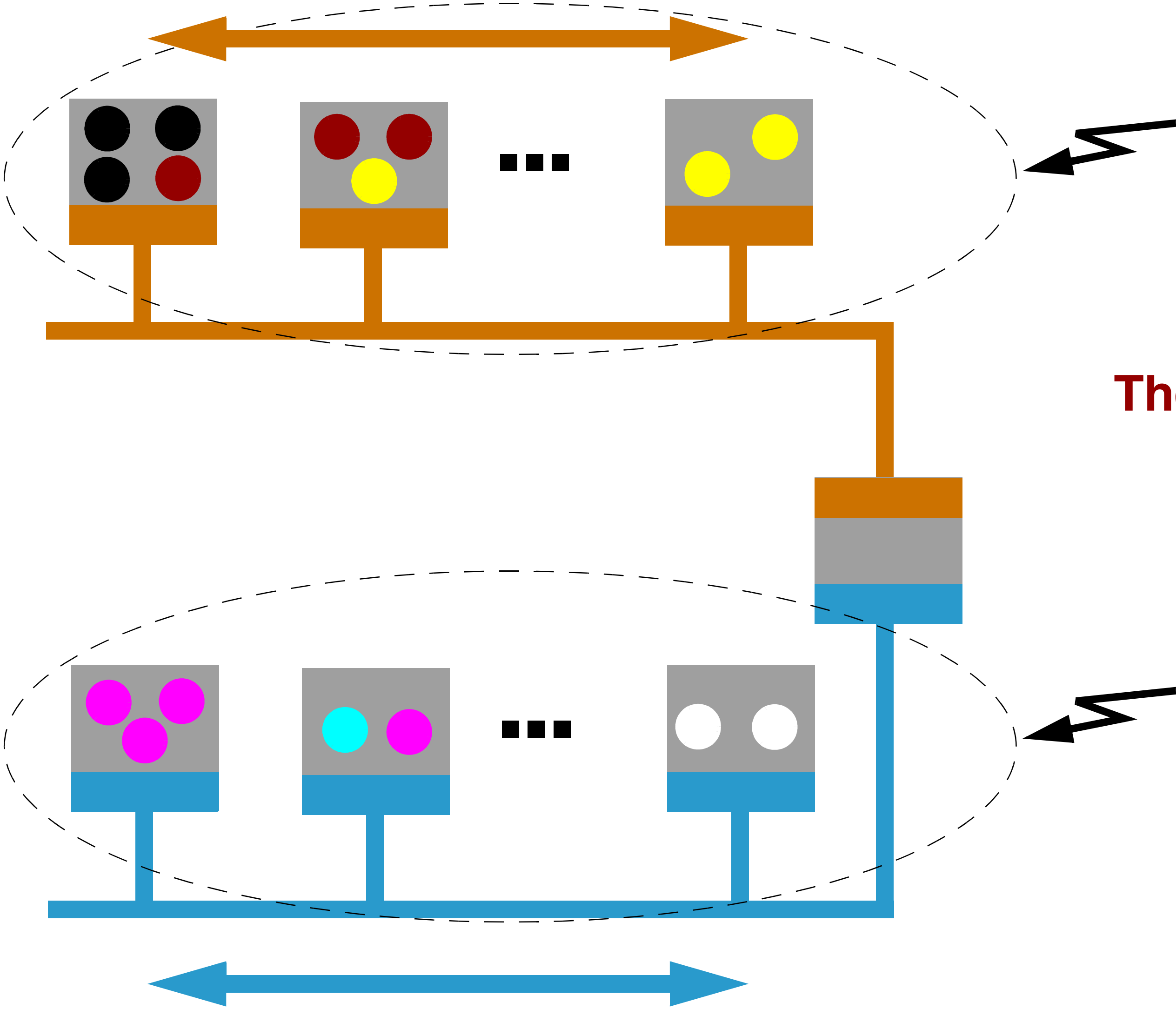


Navet et al.

Trends in Automotve Communication Systems

Proceedings of the IEEE, June 2005.

Isolated Domains



Time triggered cluster:

- TT tasks
- Static communication

The different domains are isolated.

Event triggered cluster:

- ET tasks
- Dynamic communication

Interacting Domains

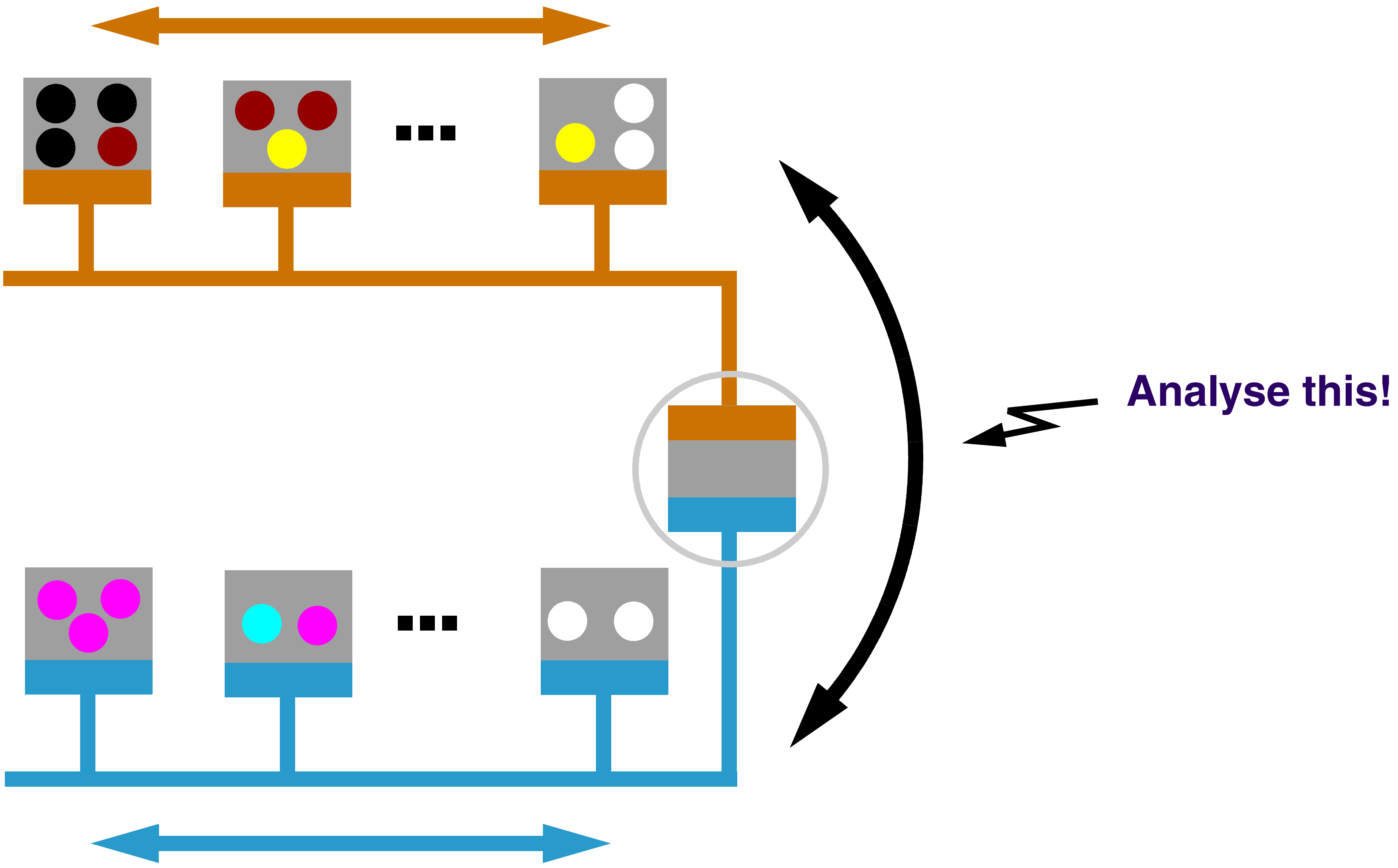
The TT & ET, Static & Dynamic domains are interacting because:

- **They share resources (node, bus)**

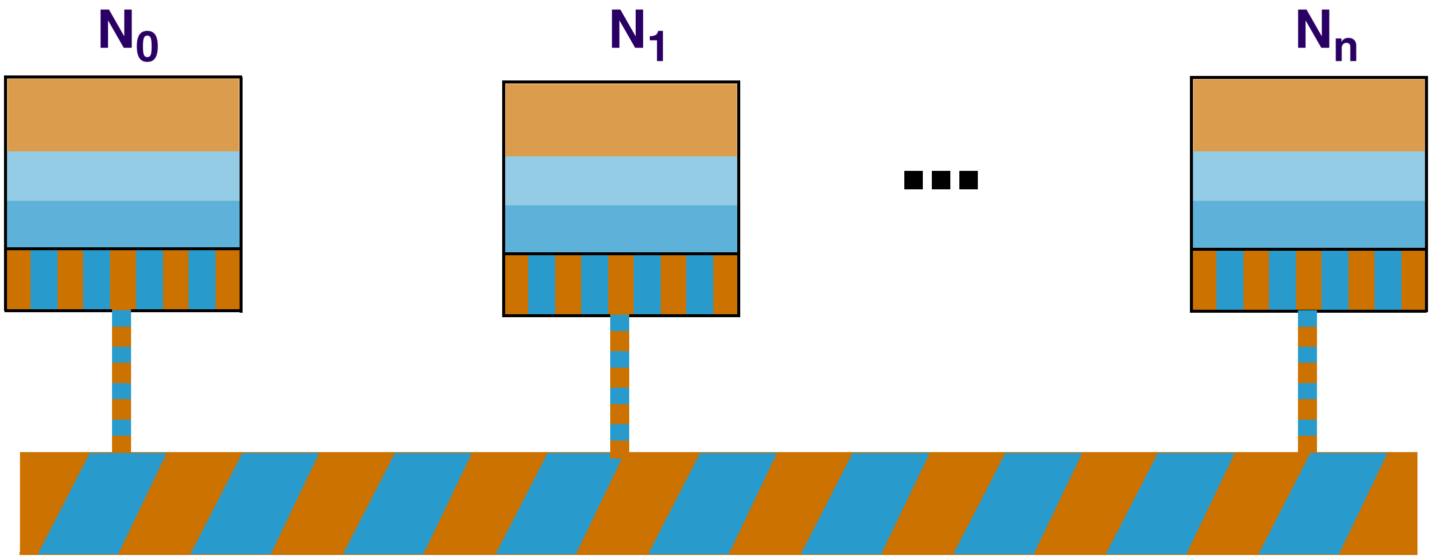
and/or

- **They communicate**

Multi-cluster Heterogeneous Distributed Architecture



Single-cluster Heterogeneous Distributed Architecture



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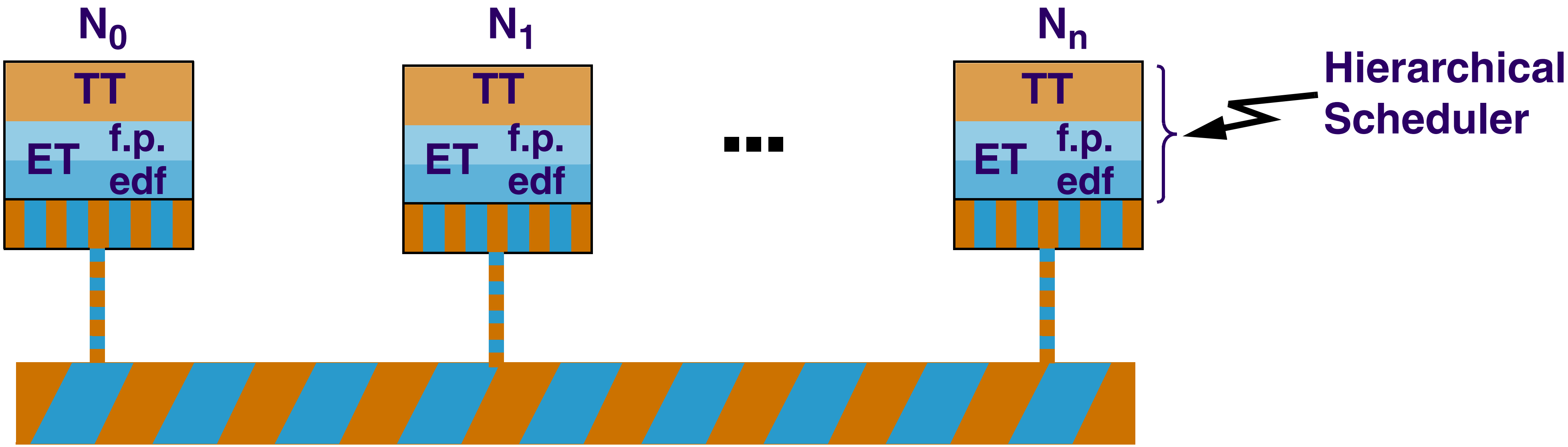

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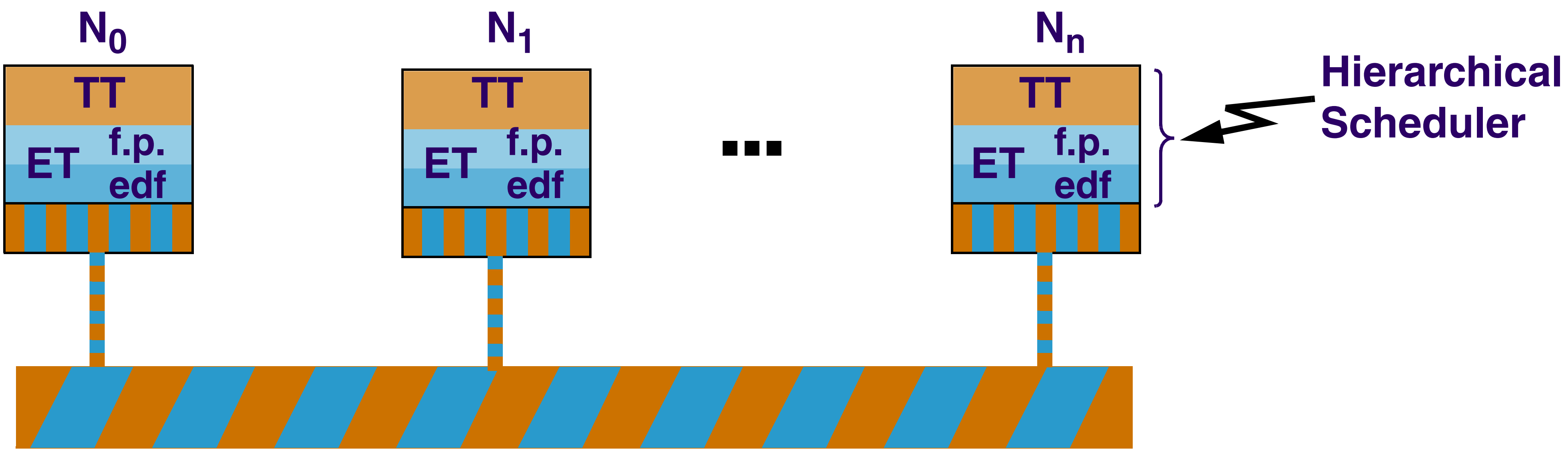
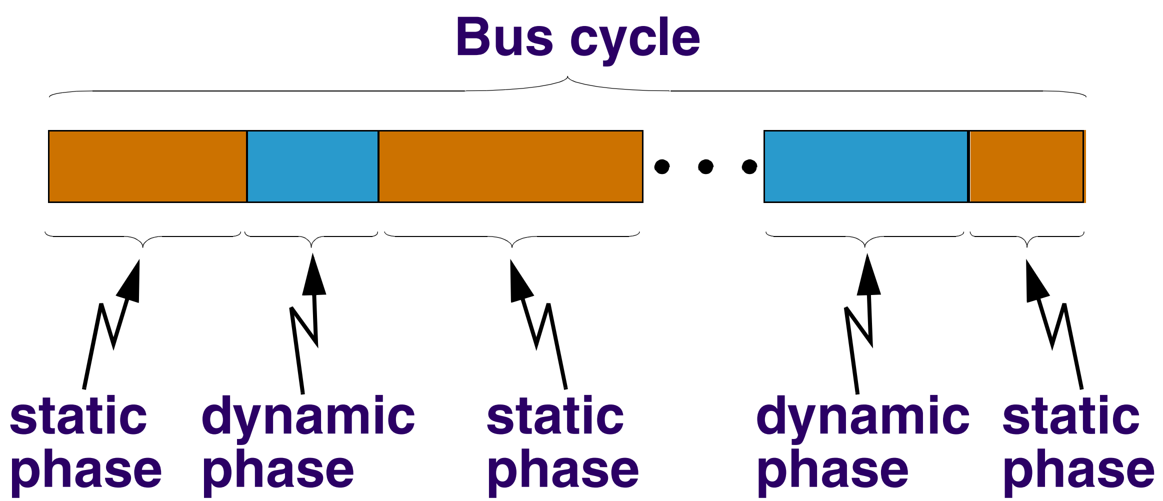


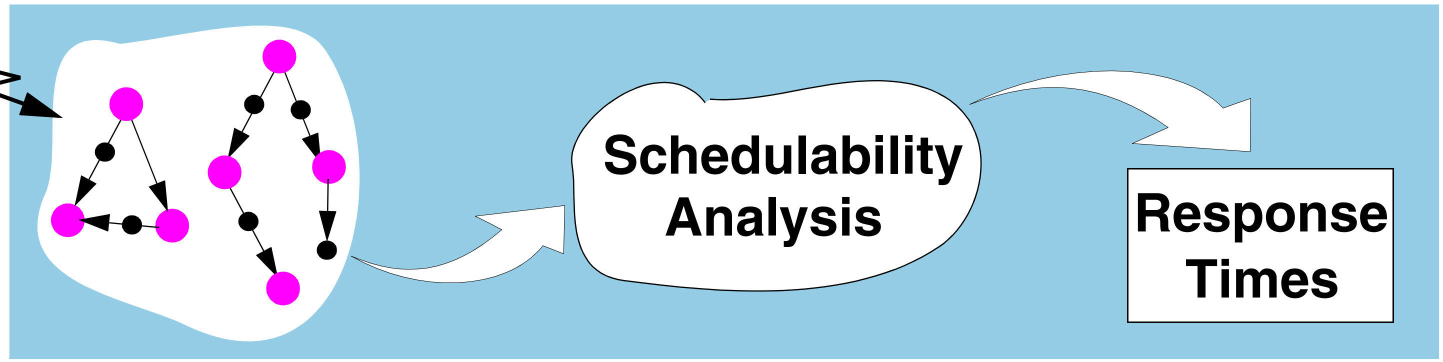


- UCM (TTP&CAN)
- FlexRay

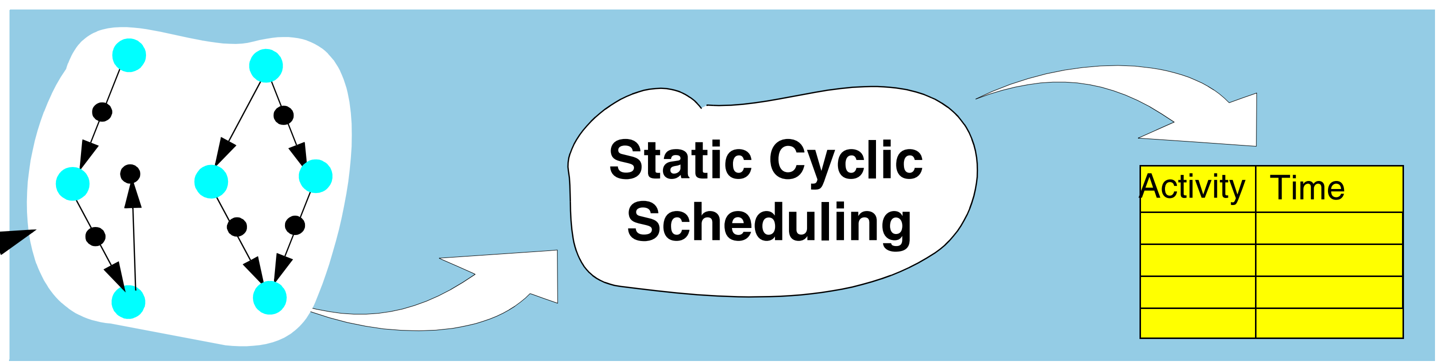
Analysis

☞ **Isolated Domains**

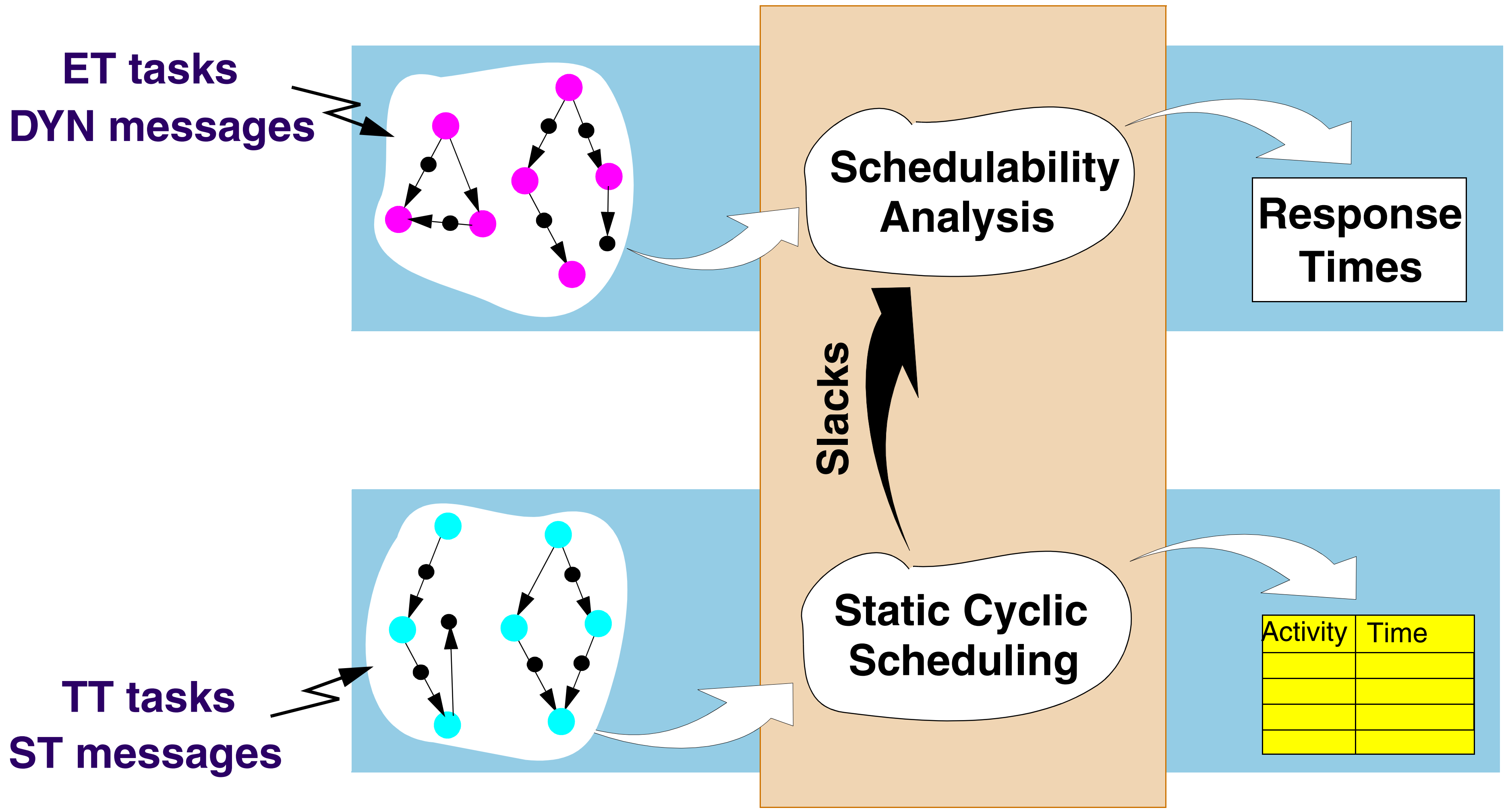
ET tasks
DYN messages



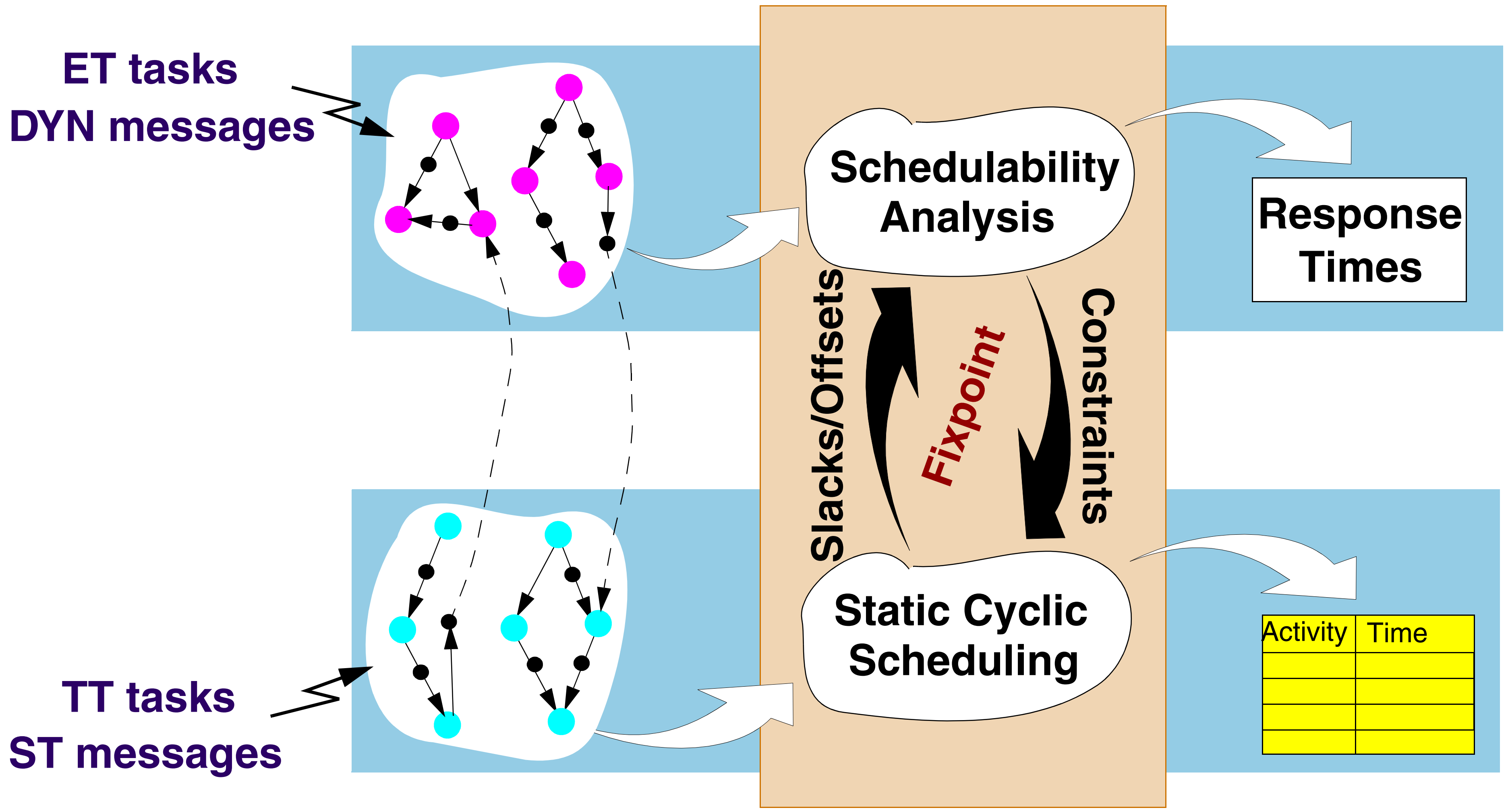
TT tasks
ST messages

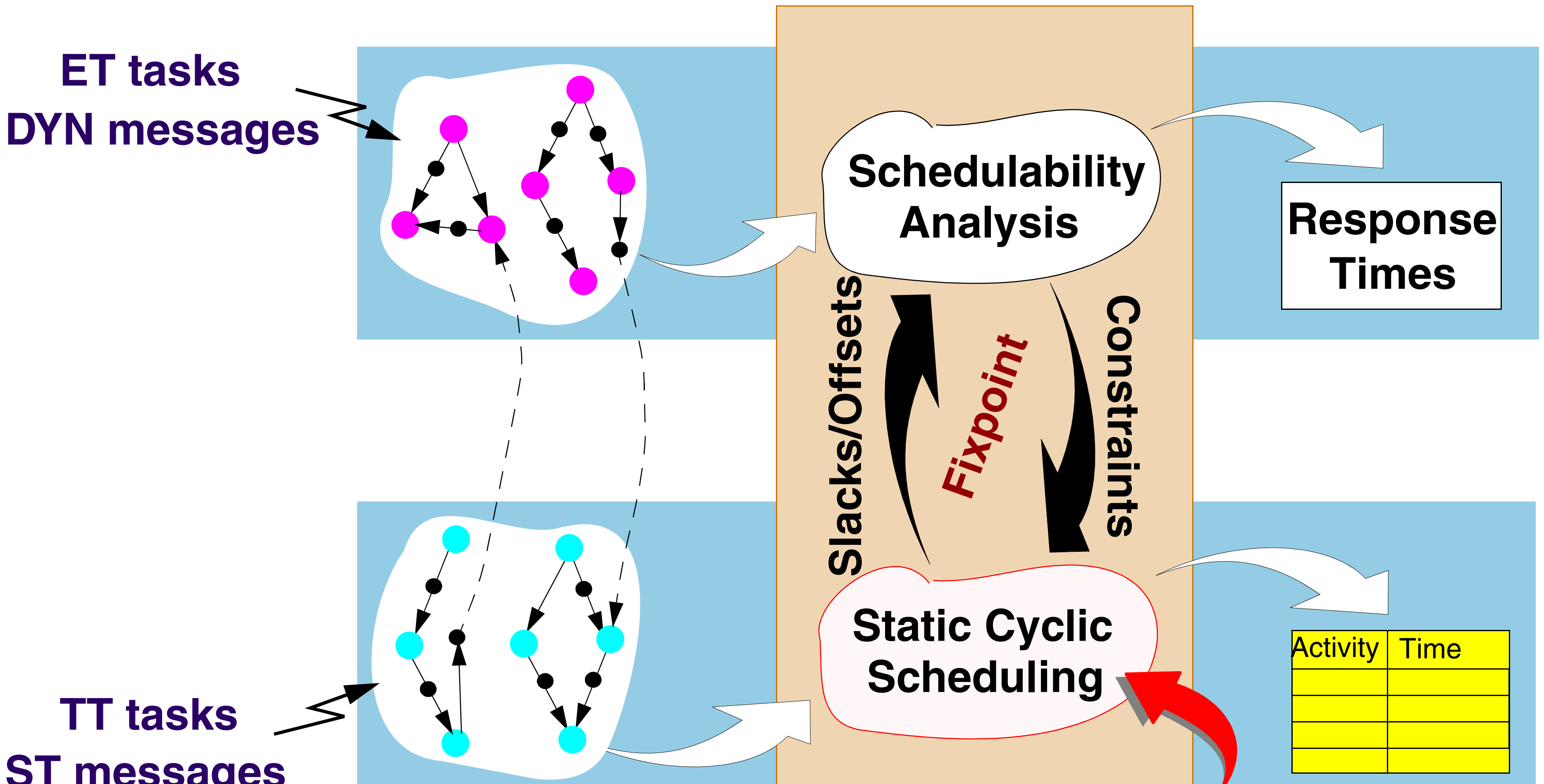


☞ **Resource sharing, no communication**



☞ **Resource sharing and communication**





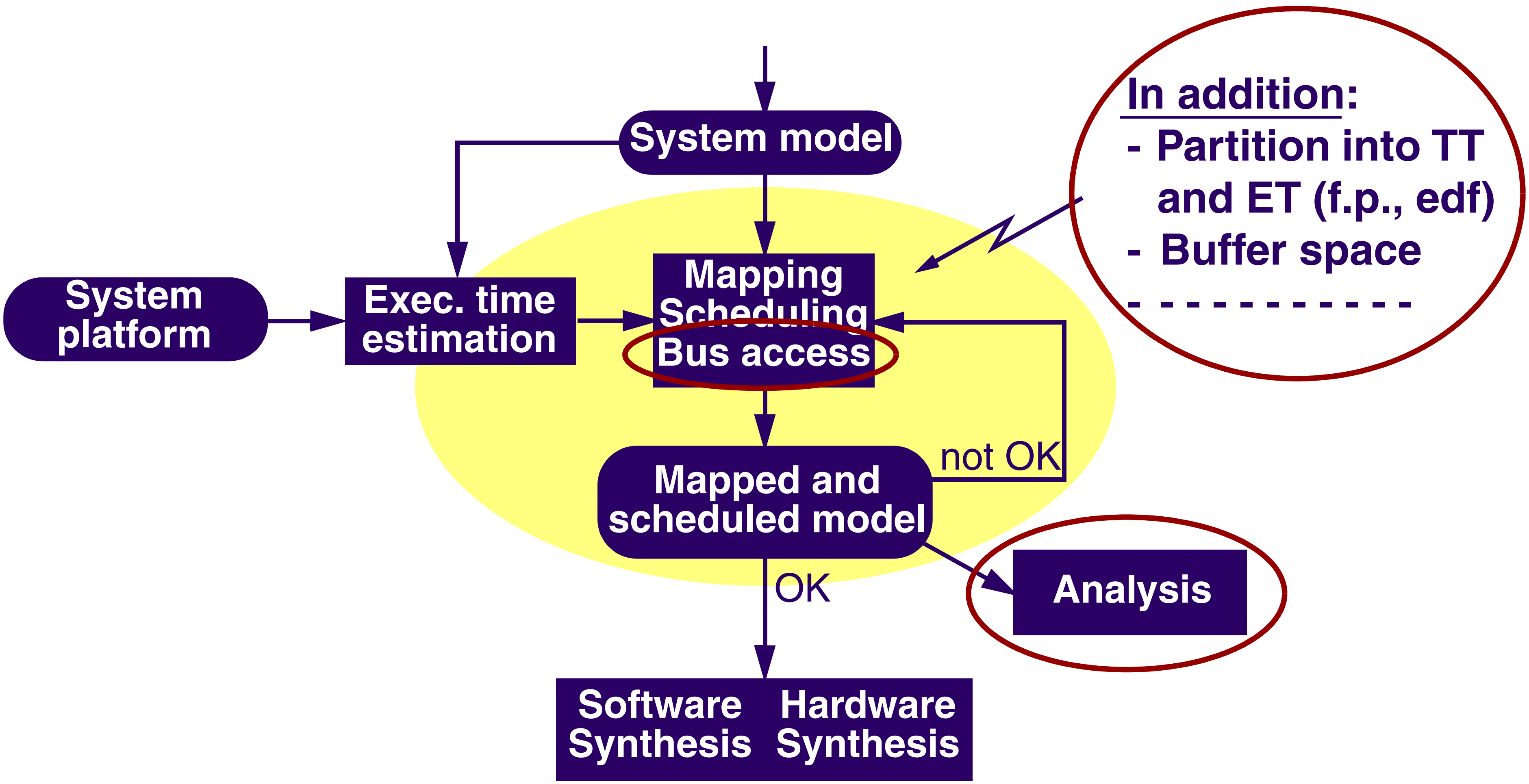
Find a schedule as “friendly” as possible towards the ET tasks!

Optimization

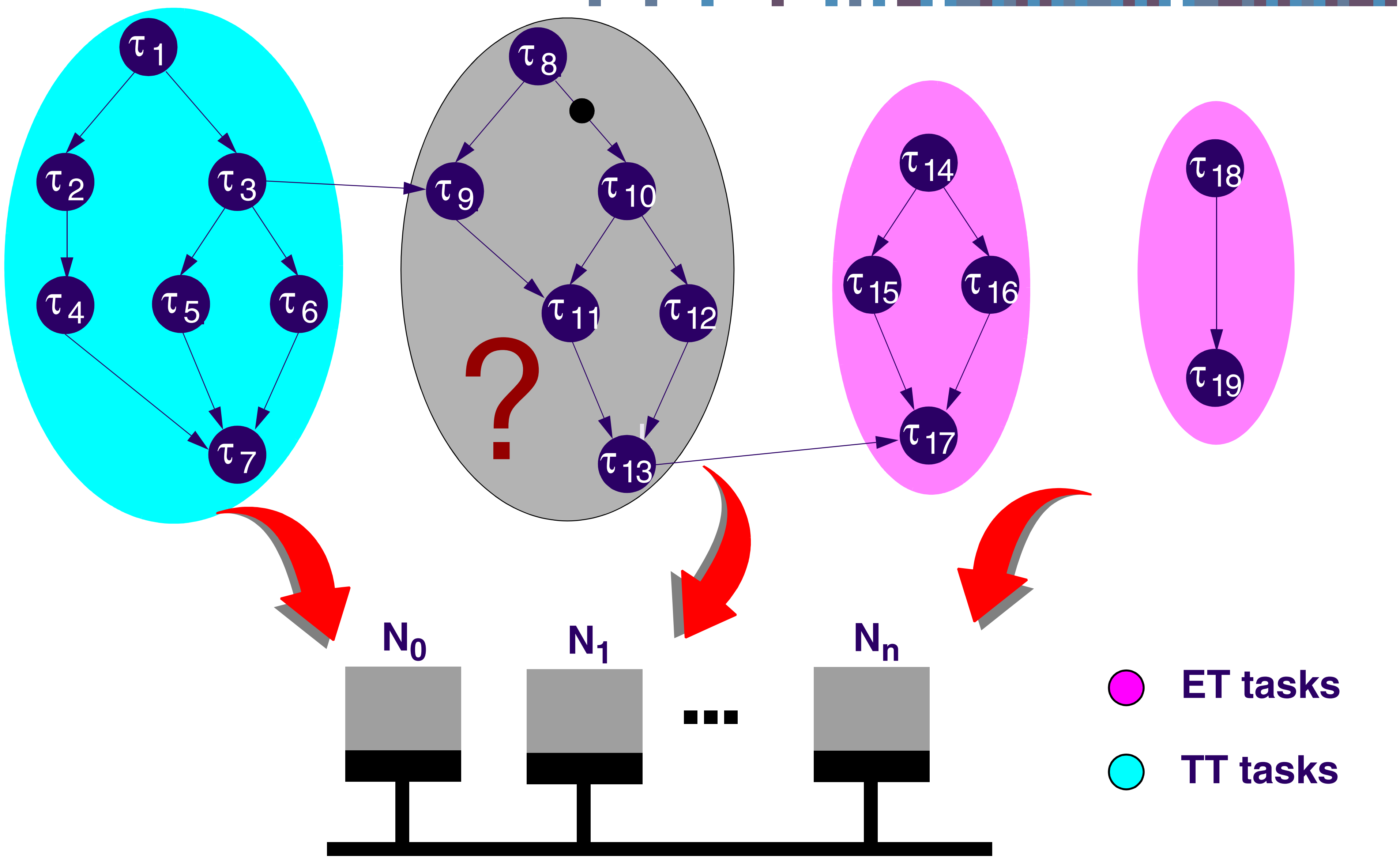
☞ **Once the analysis approach is in place, several new, specific optimization tasks can be performed (in addition to "classical" once, like task mapping):**

- **Task partitioning into TT, ET**
- **Cluster mapping**
- **Bus access optimization (static, dynamic phases)**
- **Buffer minimisation**

Optimization



Mapping & Task Partitioning



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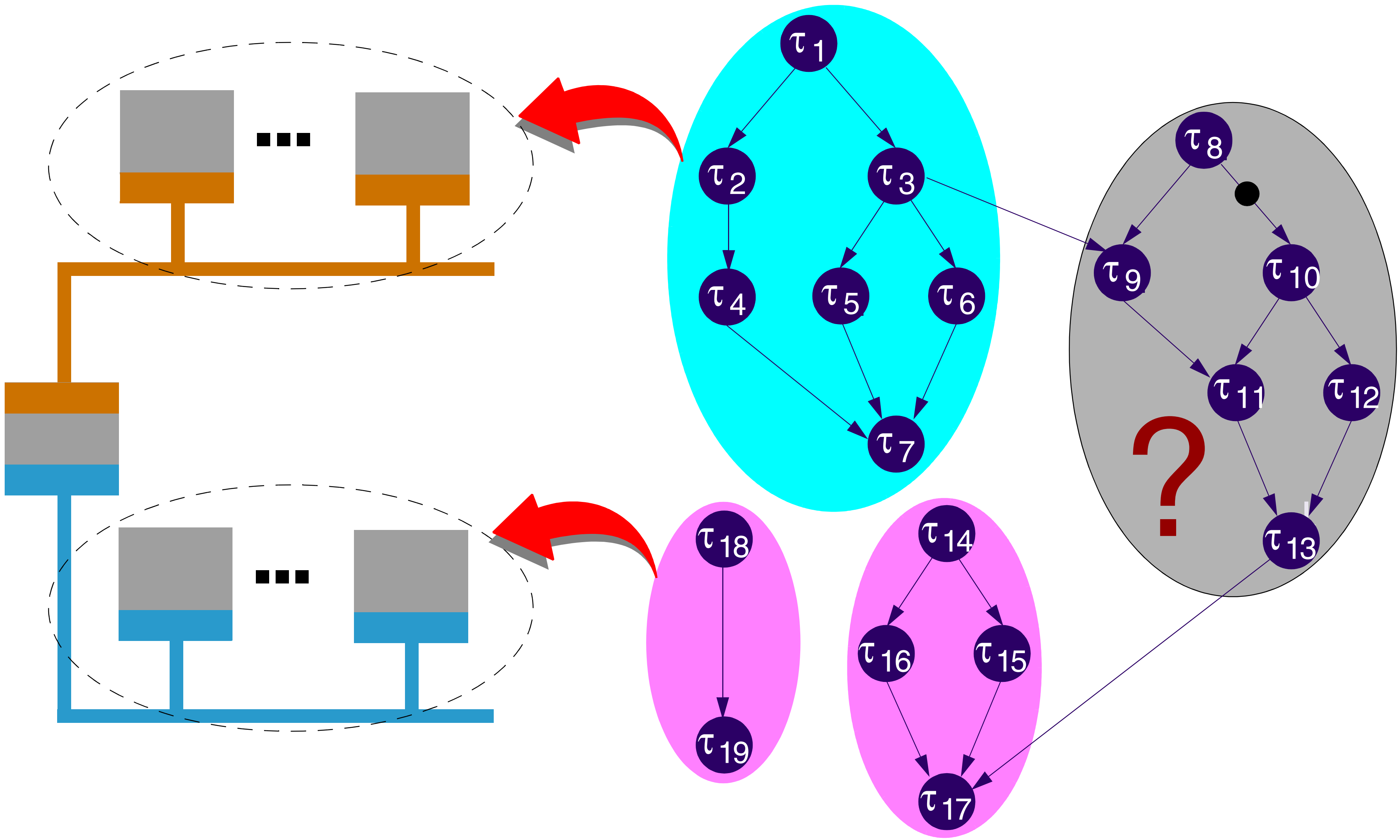

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Another Issue: Fault Tolerance

☞ **Transient faults**

- **Their number can be much larger than that of permanent faults.**

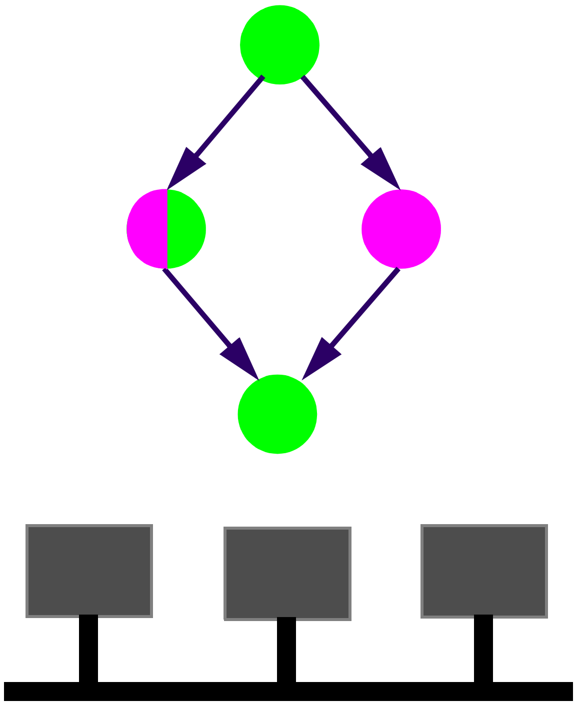
■ **Find cost-effective implementations that are fault tolerant and satisfy time constraints.**

Some Interesting trade-offs!

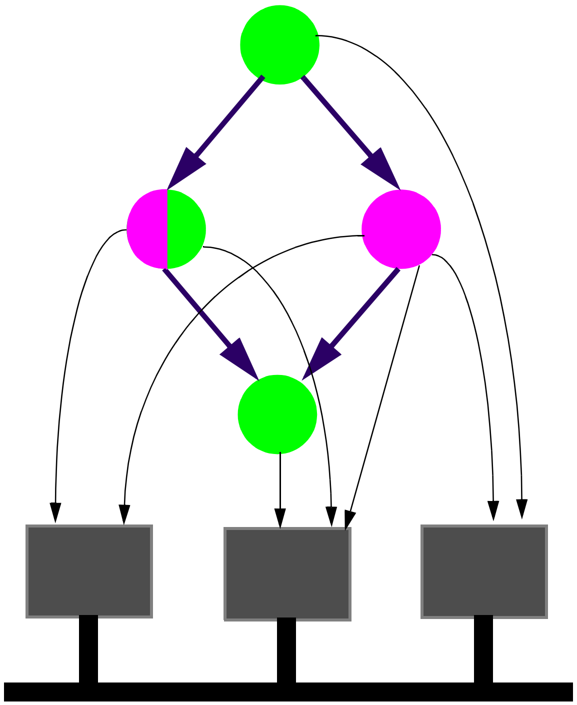
Fault Tolerance

- Decide which fault tolerance technique to apply:
  - re-execution
  - re-exution&checkpointing
  - replication

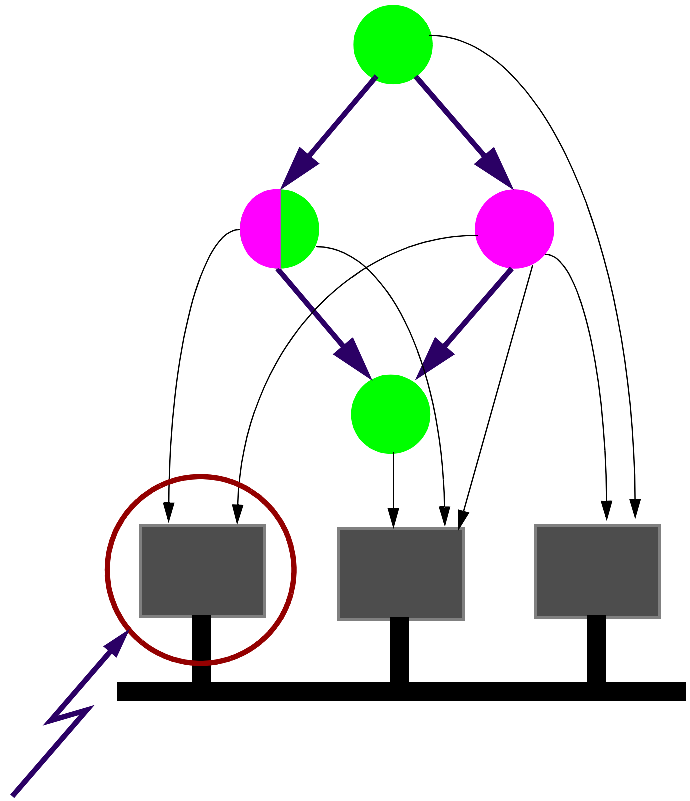
different techniques can be applied to different tasks



- Decide which fault tolerance technique to apply:
  - re-execution
  - re-exution&checkpointing
  - replication
- Map the tasks (including eventual replicas)



- Decide which fault tolerance technique to apply:
  - re-execution
  - re-exution&checkpointing
  - replication
- Map the tasks (including eventual replicas)
- Decide on transparency

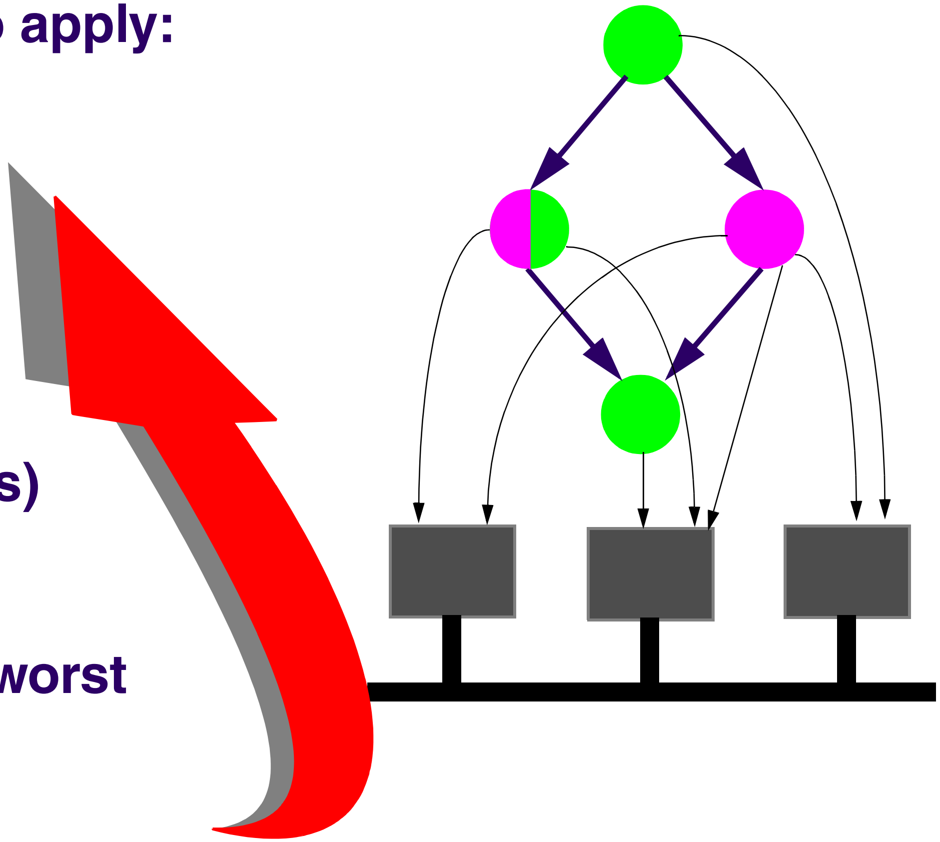


<u>Transparent</u>: The schedule of outgoing messages does not depend on occurrence of faults (faults are not visible to the outside).

Fault Tolerance

- Decide which fault tolerance technique to apply:
    - re-execution
    - re-exution&checkpointing
    - replication
- Map the tasks (including eventual replicas)
- Decide on transparency
- Do the analysis/scheduling, considering worst case number of faults (re-executions).

  Are time constraints satisfied? If not, go back!



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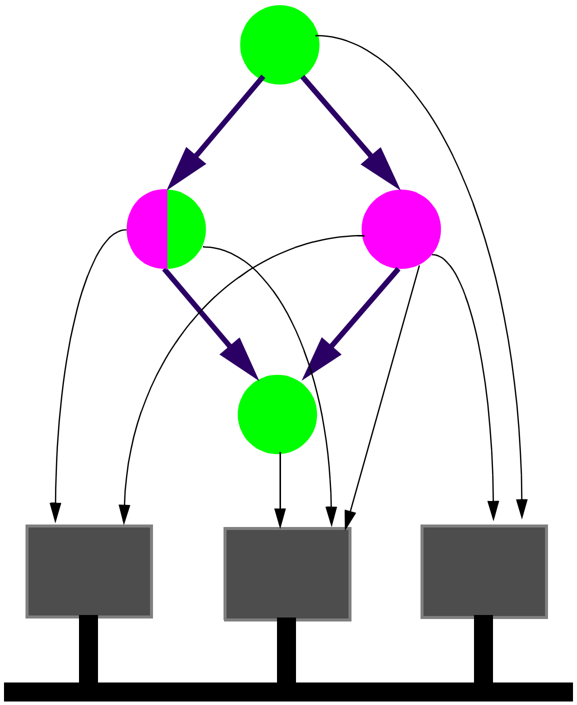

- Map the tasks (including eventual replicas)
- Decide on transparency
- Do the analysis/scheduling, considering worst case number of faults (re-executions). Are time constraints satisfied? If not, go back!

☞ Which is the optimal number of check-points?

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Distributed Soft Real-Time Systems

- **Given:**
  - ~~WCET and BCET~~ of each task
  - Dimension of messages
  - Deadlines for tasks/task graphs

☞ ~~All~~ deadlines have to be satisfied!

Distributed Soft Real-Time Systems

- **Given:**
  - Execution Time Probability Distribution Function (ETPDF) of each task
  - Dimension of messages
  - Deadlines for tasks/task graphs

☞ **A certain percentage of deadlines have to be satisfied!**

Distributed Soft Real-Time Systems

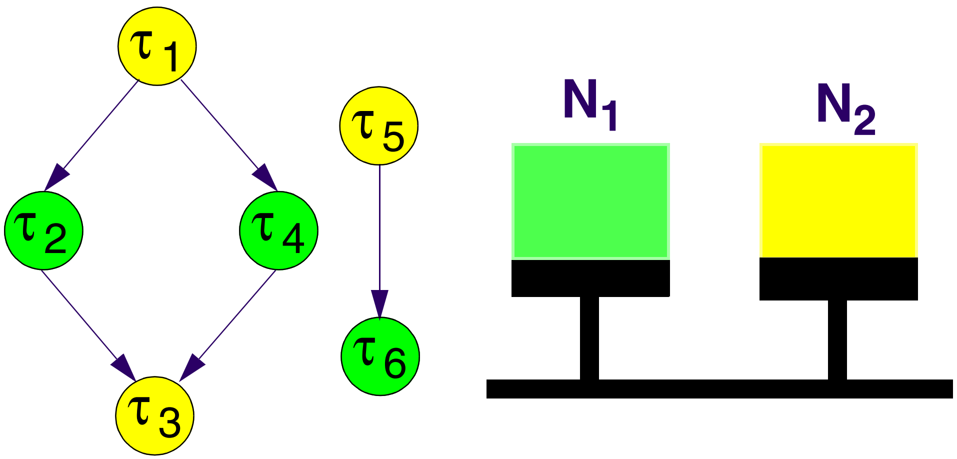
- **Given:**
  - Execution Time Probability Distribution Function (ETPDF) of each task
  - Dimension of messages
  - Deadlines for tasks/task graphs

☞ **A certain percentage of deadlines have to be satisfied!**

- **Problems:**
  - Determine the percentage of missed deadlines for each task/task graph.
  - Optimize task mapping and priority assignment, such that a required percentage of satisfied deadlines is achieved.

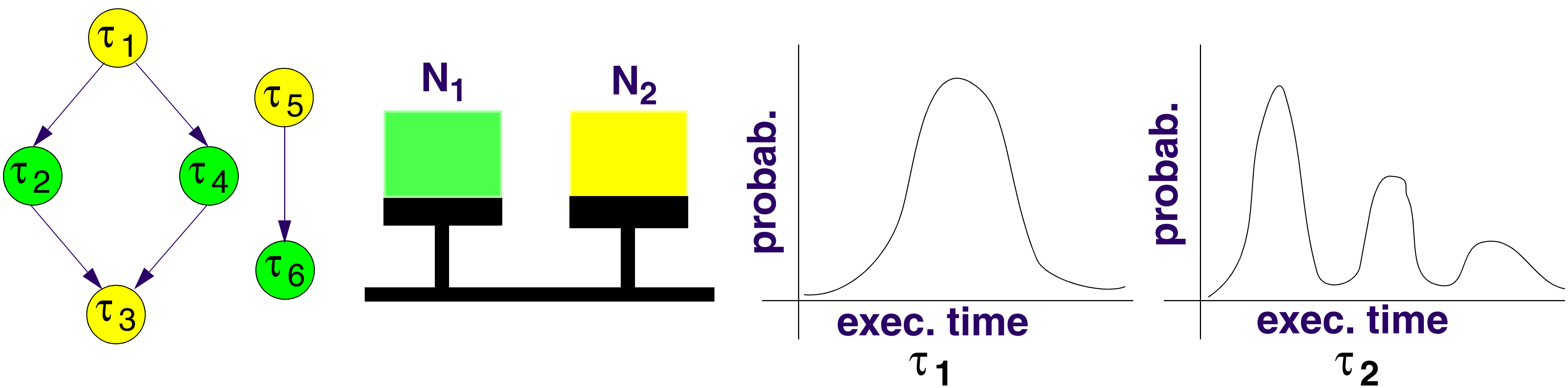
Input:

- **Set of mapped task graphs, periods, deadlines, priorities.**



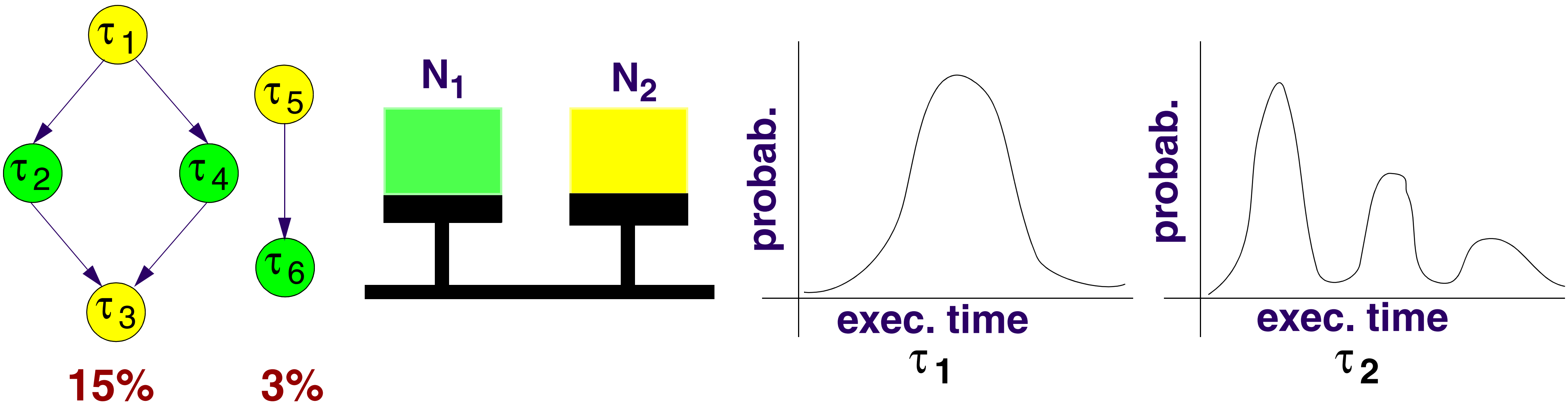
Input:

- Set of mapped task graphs, periods, deadlines, priorities.
- Set of execution times probability density functions.
- Scheduling policy.



Output:

- Ratio of missed deadlines per task/task graph



Main Problem

- The main problem is **Complexity** (in terms of analysis time and memory).

    - Applying straight-forward solutions is possible

        - only for very(!) small applications.

        and/or

        - for very particular cases (e.g. exponential distributions).

Approaches

- An exact method for schedulability analysis, efficiently applicable (but not limited) to monoprocessor systems.

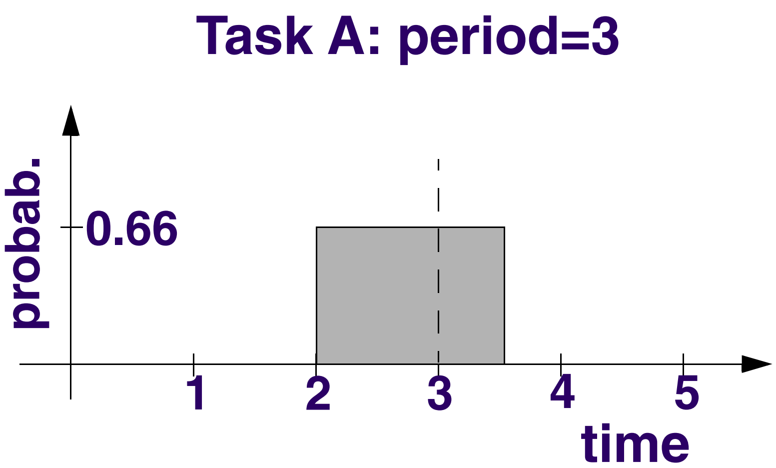
- An method for schedulability analysis, trading analysis efficiency for result accuracy; efficiently applicable to multiprocessors.

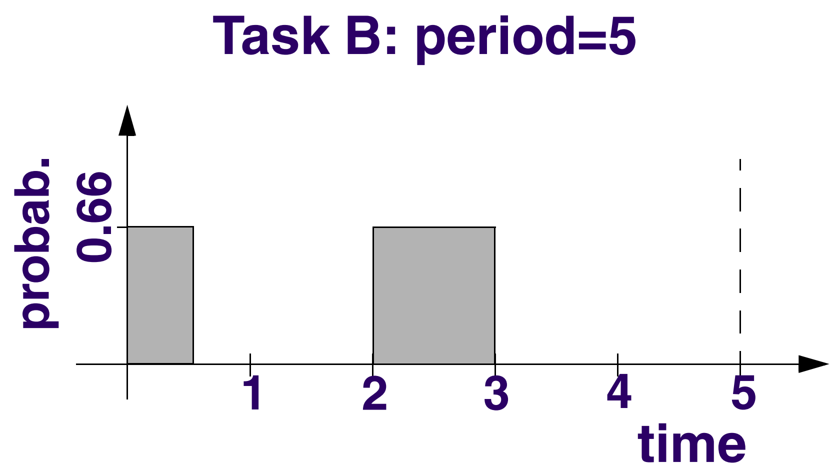
- A very fast, approximate analysis, to be used inside an optimization loop.

Stochastic Process Construction

- Analyse of the underlying stochastic process.
  - A state of the process should capture enough information to be able to generate the next states and to compute the corresponding transition probabilities

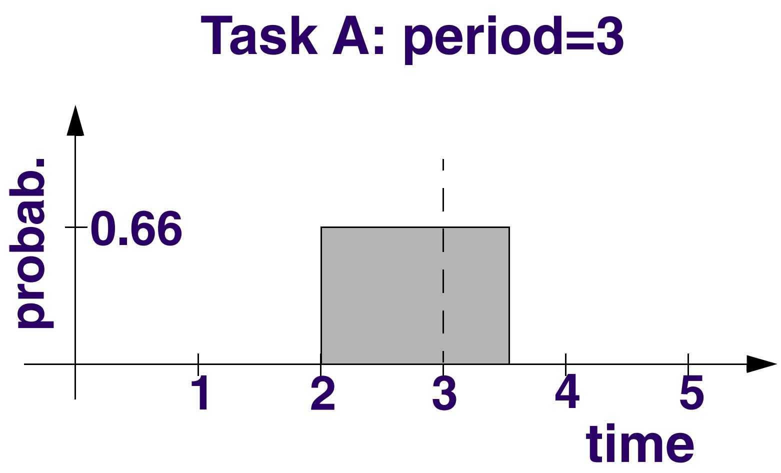
Stochastic Process Construction

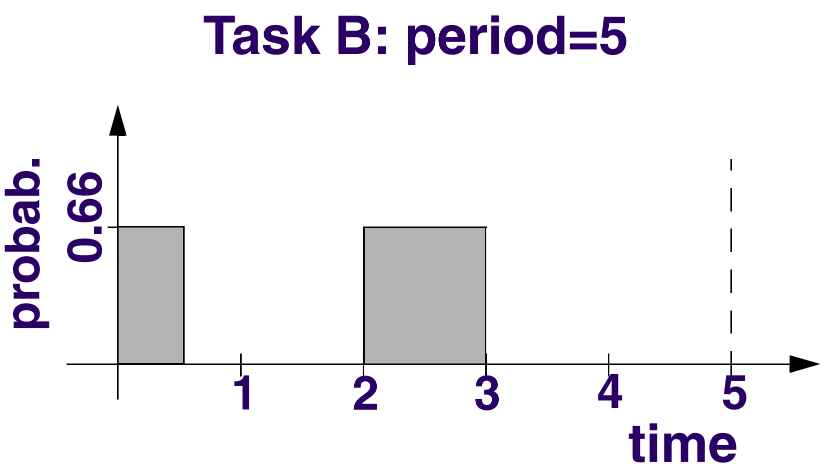


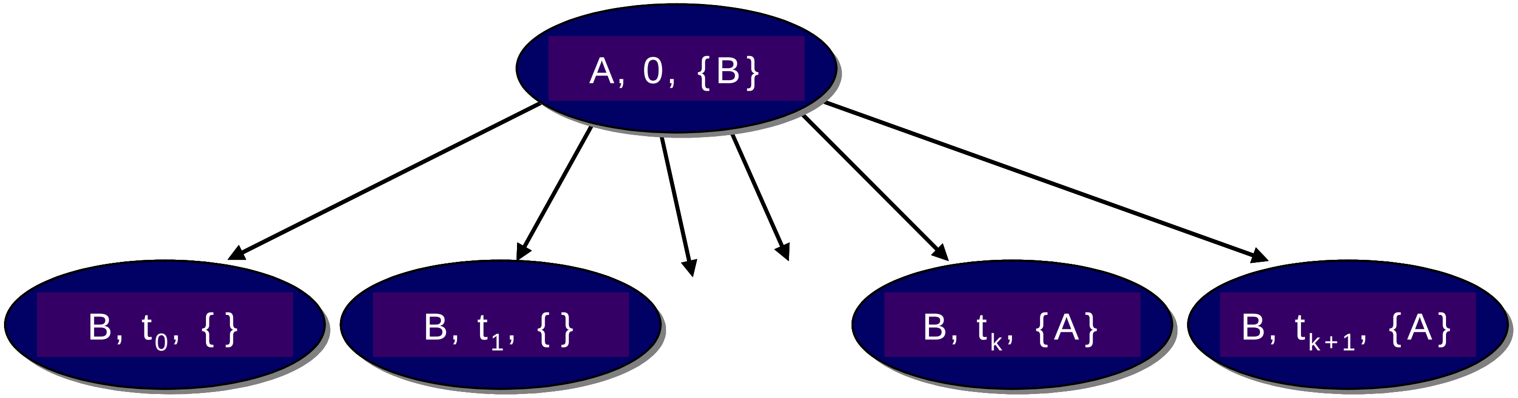


☞ EDF scheduling

Stochastic Process Construction

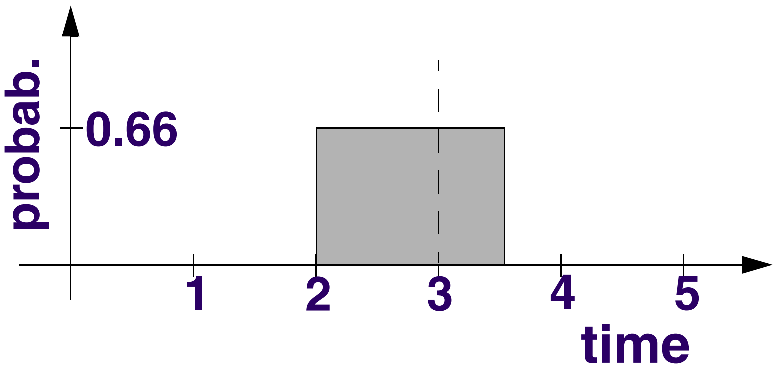


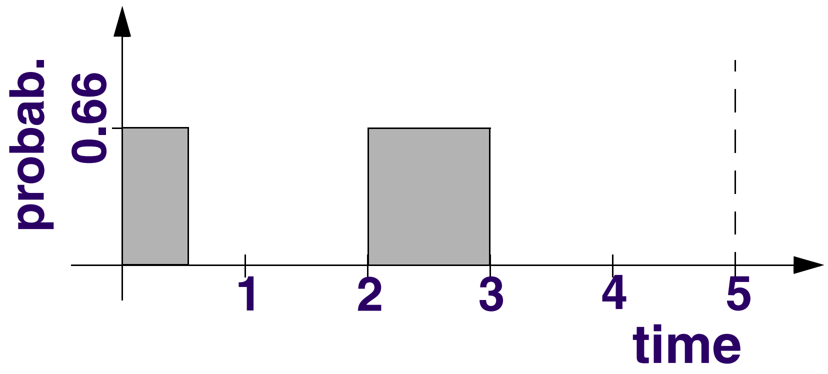


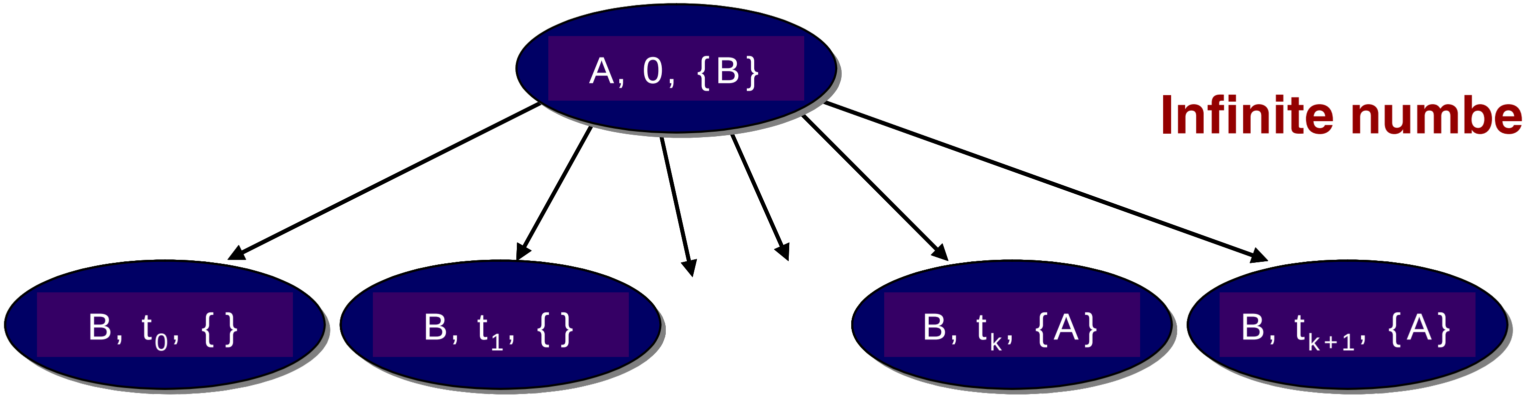


Stochastic Process Construction

Task A: period=3 **Task B: period=5**



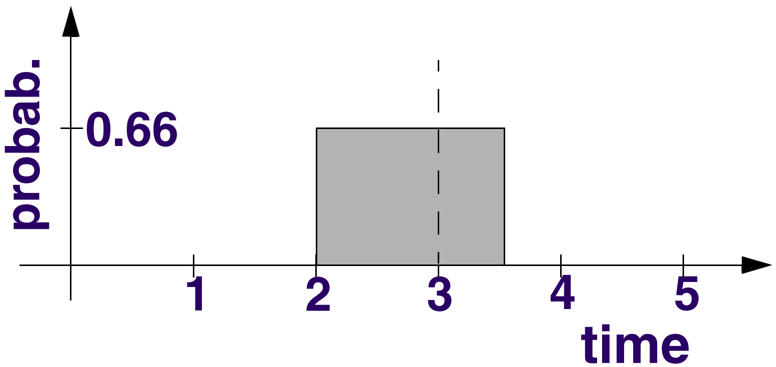




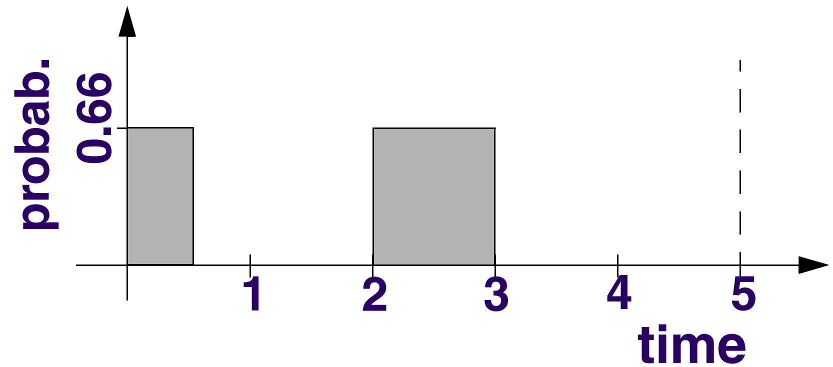
Infinite number of states!

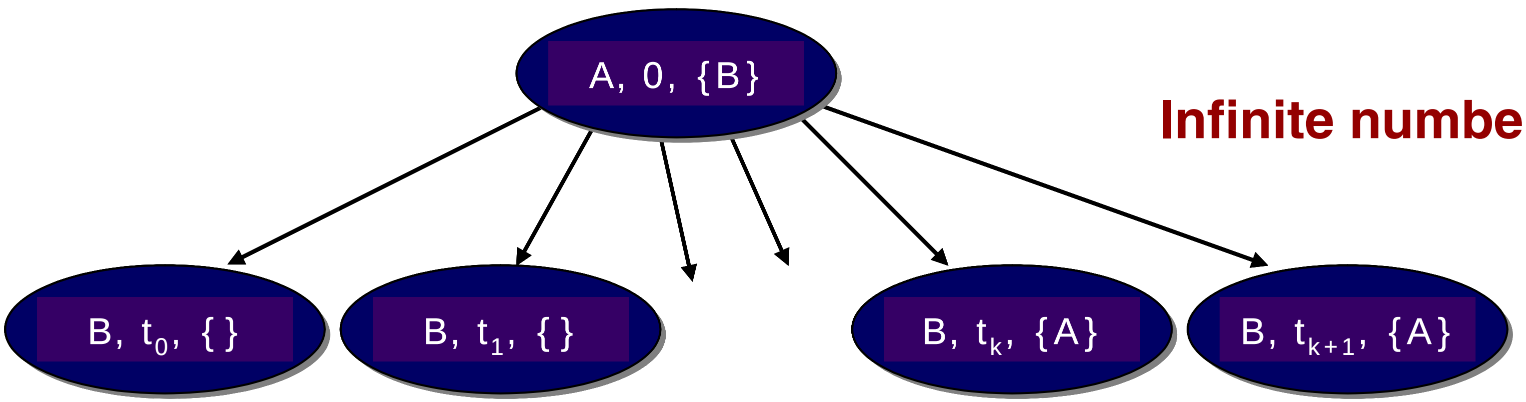
Stochastic Process Construction

Task A: period=3



Task B: period=5





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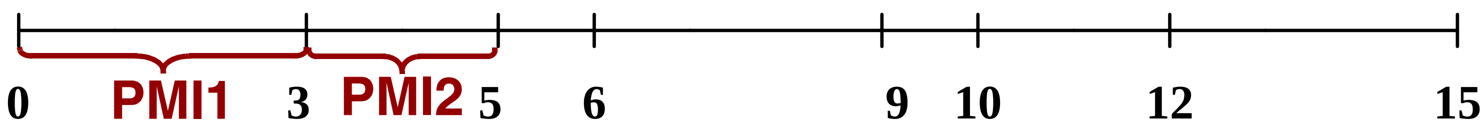
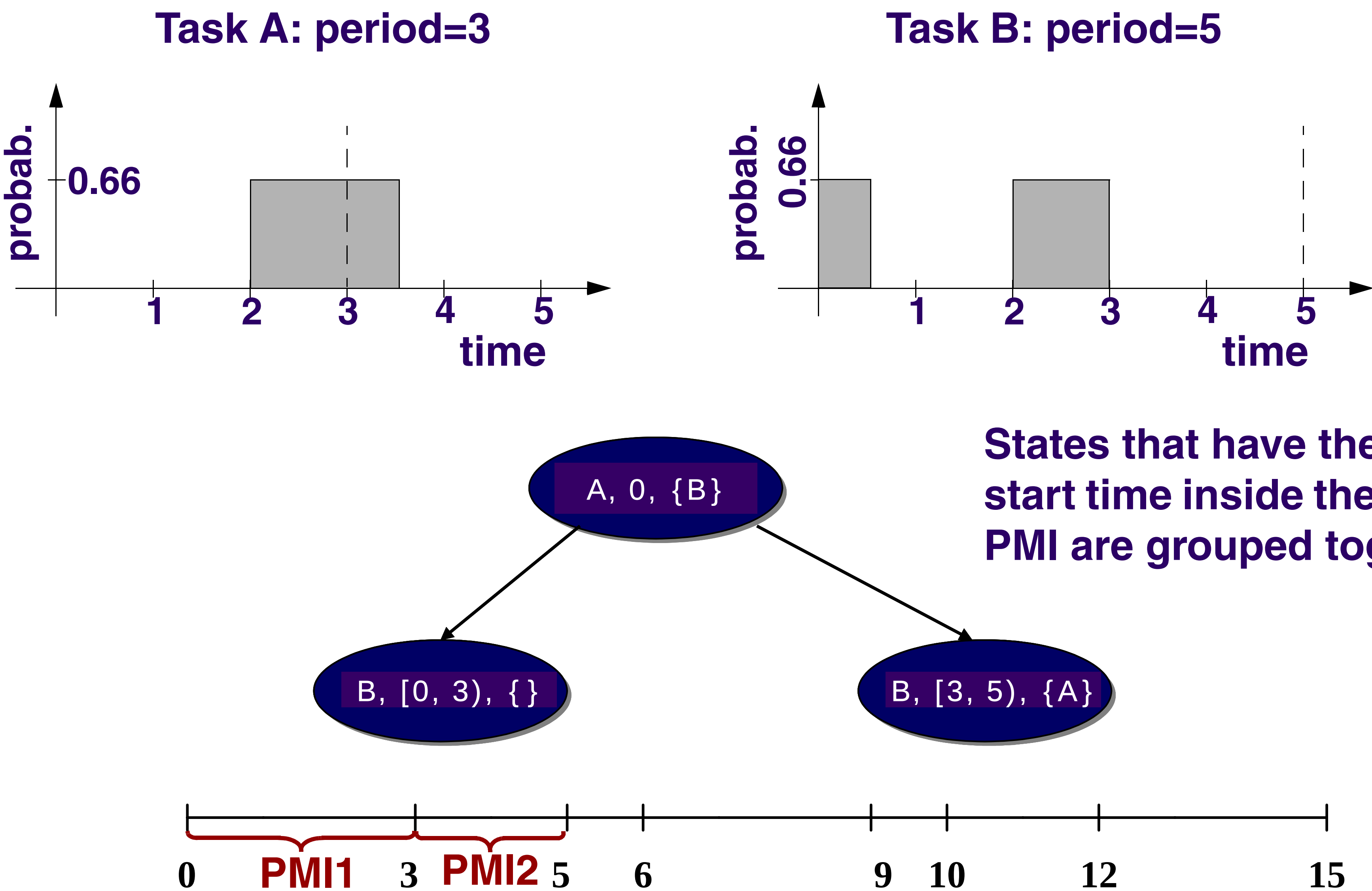


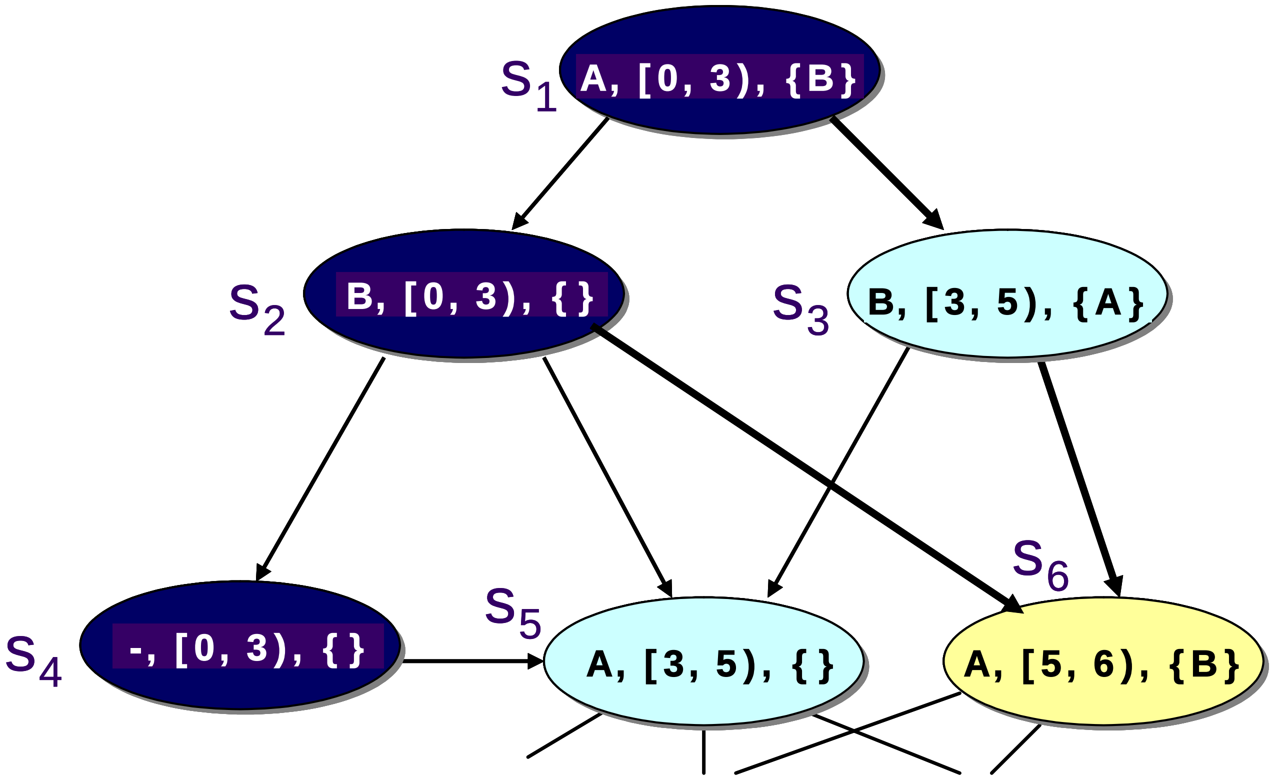
Stochastic Process Construction



States that have their start time inside the same PMI are grouped together.

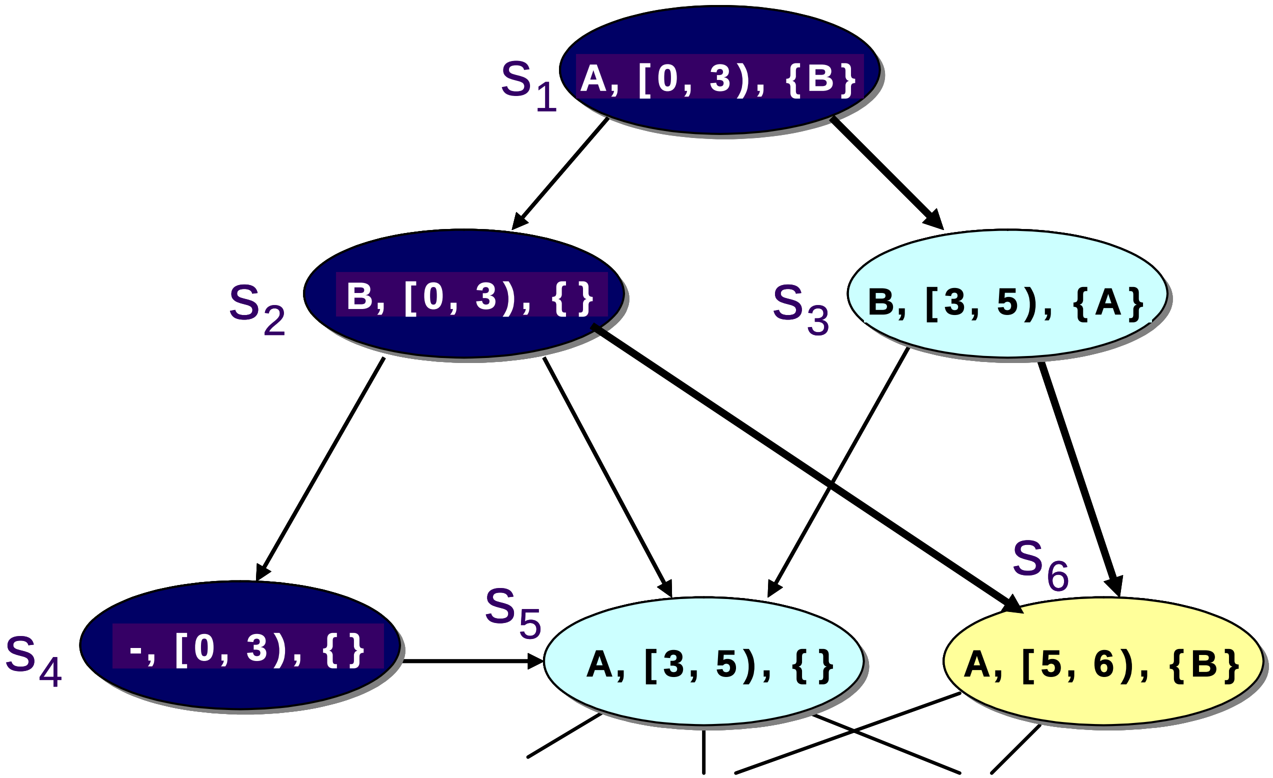
Stochastic Process Construction

☞ **The Stochastic process is constructed and probabilities corresponding to individual states are calculated by convolution.**



Stochastic Process Construction

- The Stochastic process is constructed and probabilities corresponding to individual states are calculated by convolution.
- **Good News:** Process construction and analysis are performed simultaneously. Only a (very small) sliding window of the states has to be stored in memory at any time.



Limitation

- The number of states increases very much in the case of *interacting tasks implemented on multiprocessor systems*.

- We need to avoid
  - storing explicitly the distribution of residual exec. time in each state;
  - calculation of the convolutions.

Multiprocessor Approach

The generalised ETPDFs are approximated by weighted sums of exponential functions (Coxian approximation).

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Larger, but much easier to analyse

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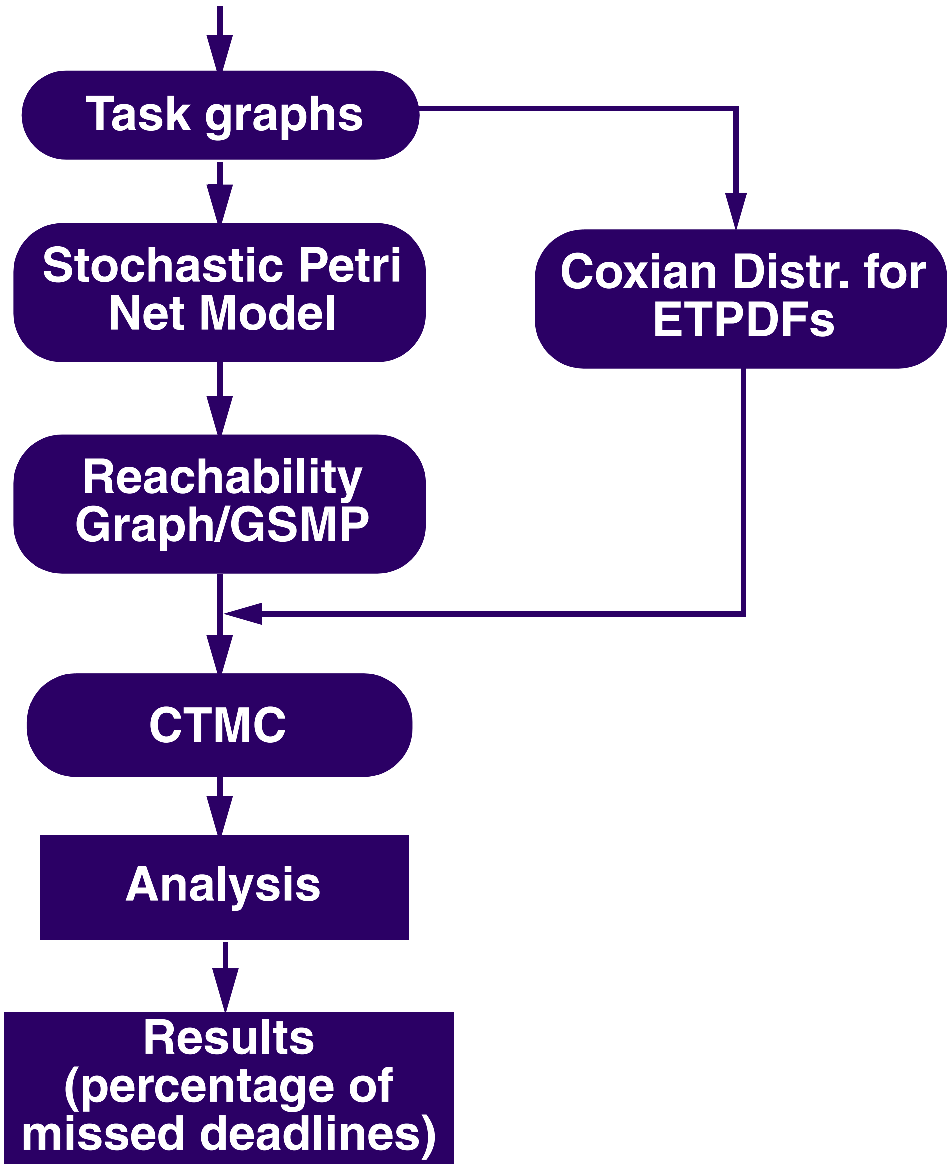
↓

The initial generalised semi-Markov process is transformed into a continuous time Markov chain.

- ☞ **Good News**: **The whole matrix, corresponding to the complete model, has *not* to be stored in memory; it is generated on the fly, from terms expressed as small matrices.**
- ☞ **Accuracy can be traded for analysis time/memory.**

Multiprocessor Approach



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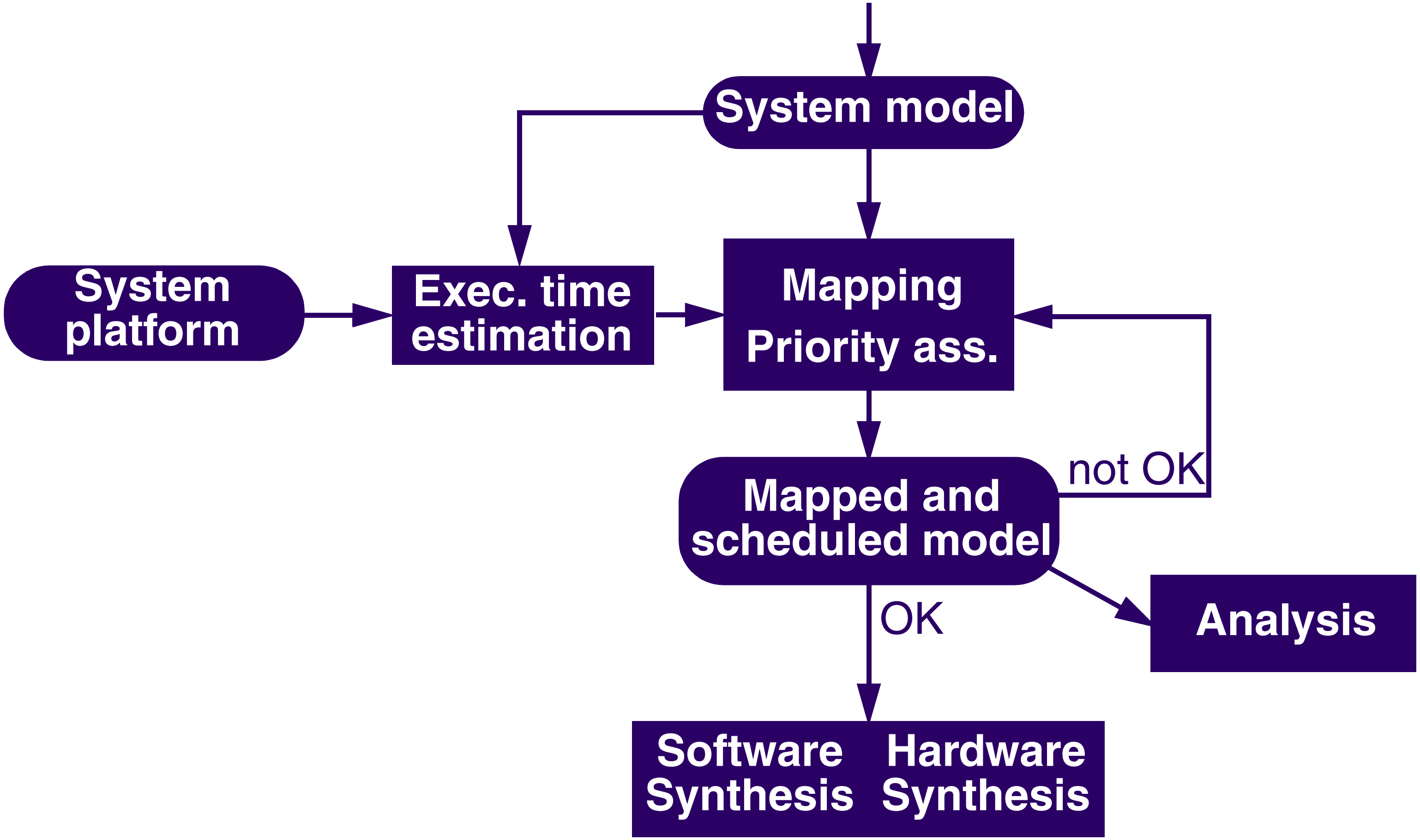
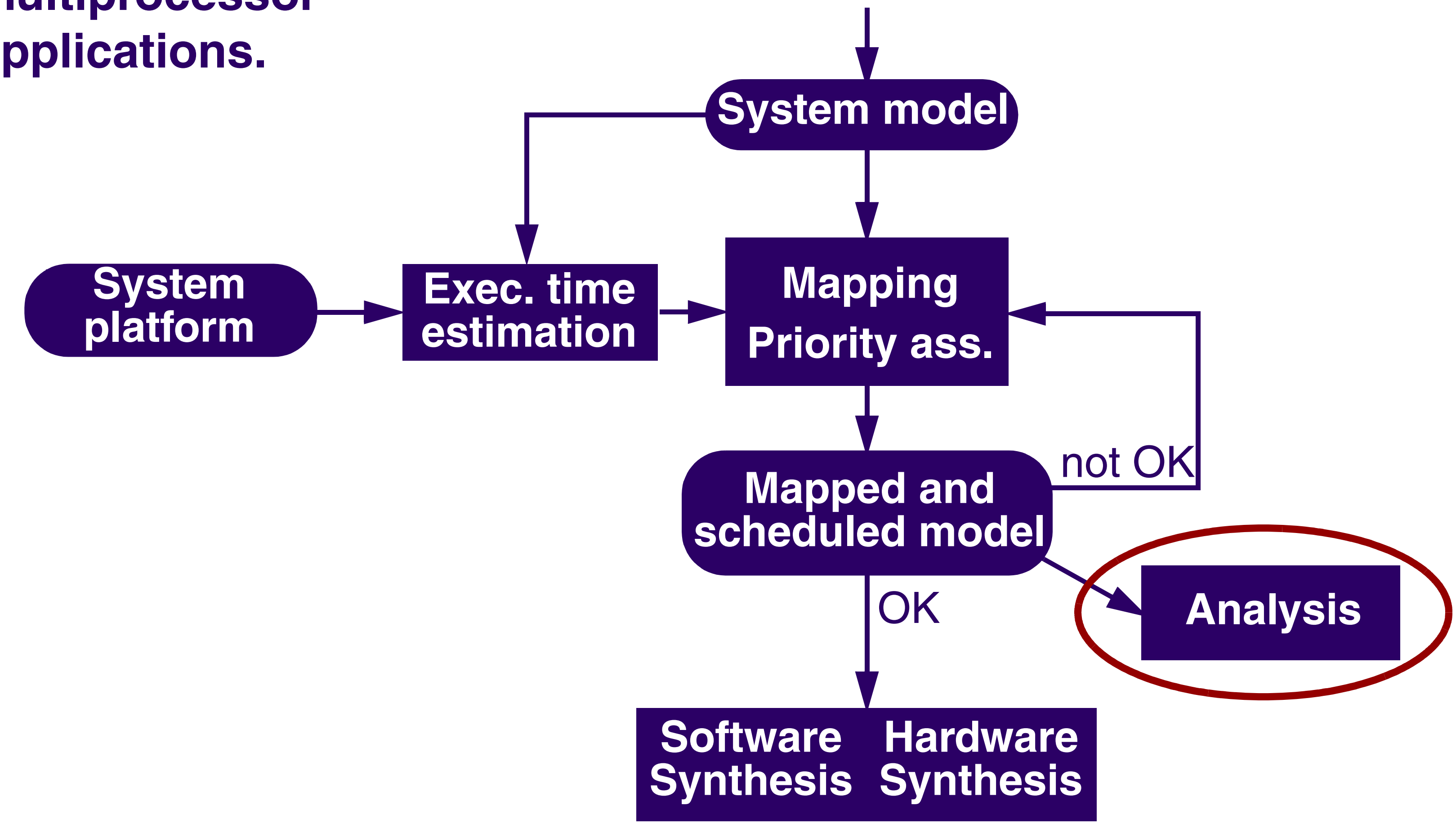


System Optimization

☞ The presented analysis approach works for large multiprocessor applications.

But

☞ It is too slow to be used inside an optimization loop.



- ☞ An approximate analysis method of polynomial complexity has been developed.

- **Basic idea:**
  - Weak dependencies among the random variables have been neglected.

↓

Very fast analysis, sufficiently accurate to guide the design space exploration.

System Optimization

If you optimize your system to minimise average or worst case execution time

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then

YOU ARE VERY WRONG!!!

Conclusions

- Distributed embedded systems are becoming common.

- They are communication dominated and heterogeneous.
- They have to be safe (fault tolerance).

- Hard distributed real-time systems.
- Soft distributed real-time systems.

} How to guarantee timing constr.?

- Analysis (in particular timing) is difficult, but possible.

  Simulation is not the right solution!

- It is not sufficient to analyse! Help the designer to implement a cost effective system that satisfies the imposed constraints!

  Efficient optimization tools are needed.