Software (System) Synthesis: Raising the Level of Abstraction

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Outline

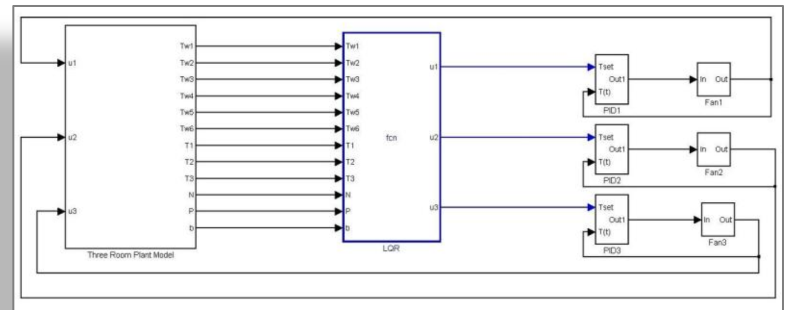
- Lesson learned from logic synthesis
- ‘Software’ Synthesis Flow and Algorithms
- Case Studies

MBD: Code generation

e.g. Mathworks RTW, dSpace TargetLink

High level input models

(Simulink, Modelica, …)



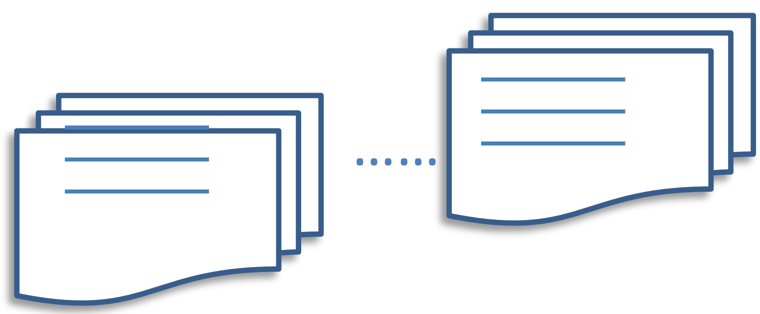
Direct code generation

- No significant restructuring

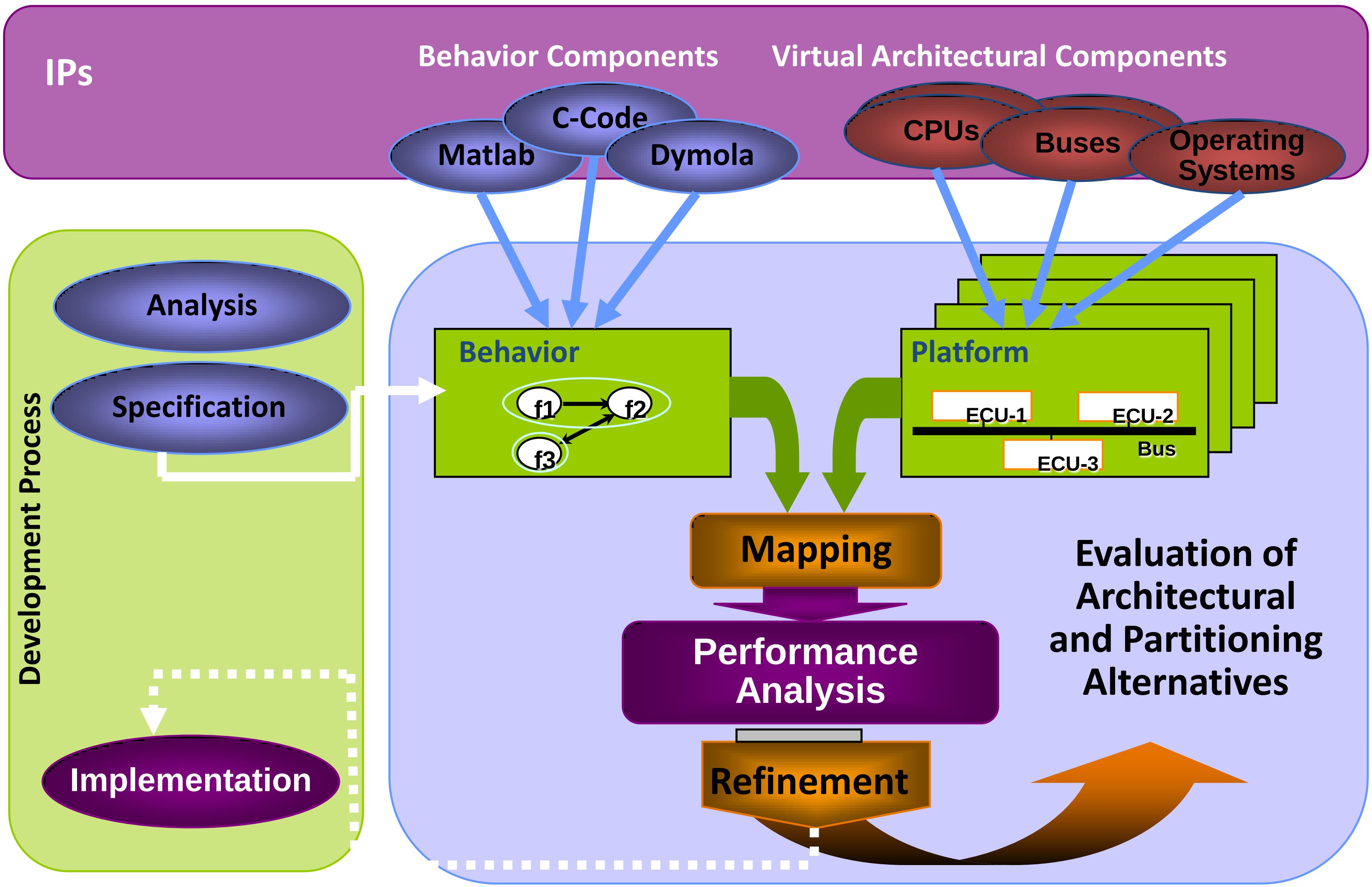
- Low level optimization

- Manual partition

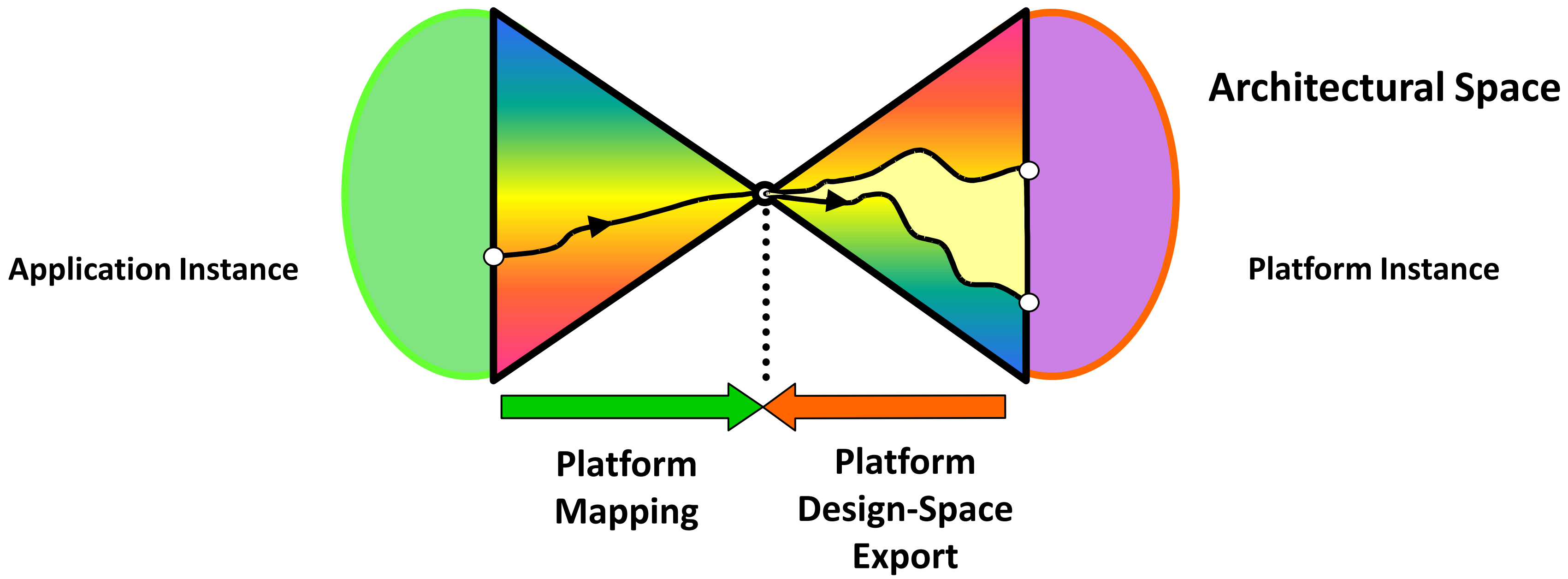
Target code



Separation of Concerns (ca. 1990)



Platform-Based Design

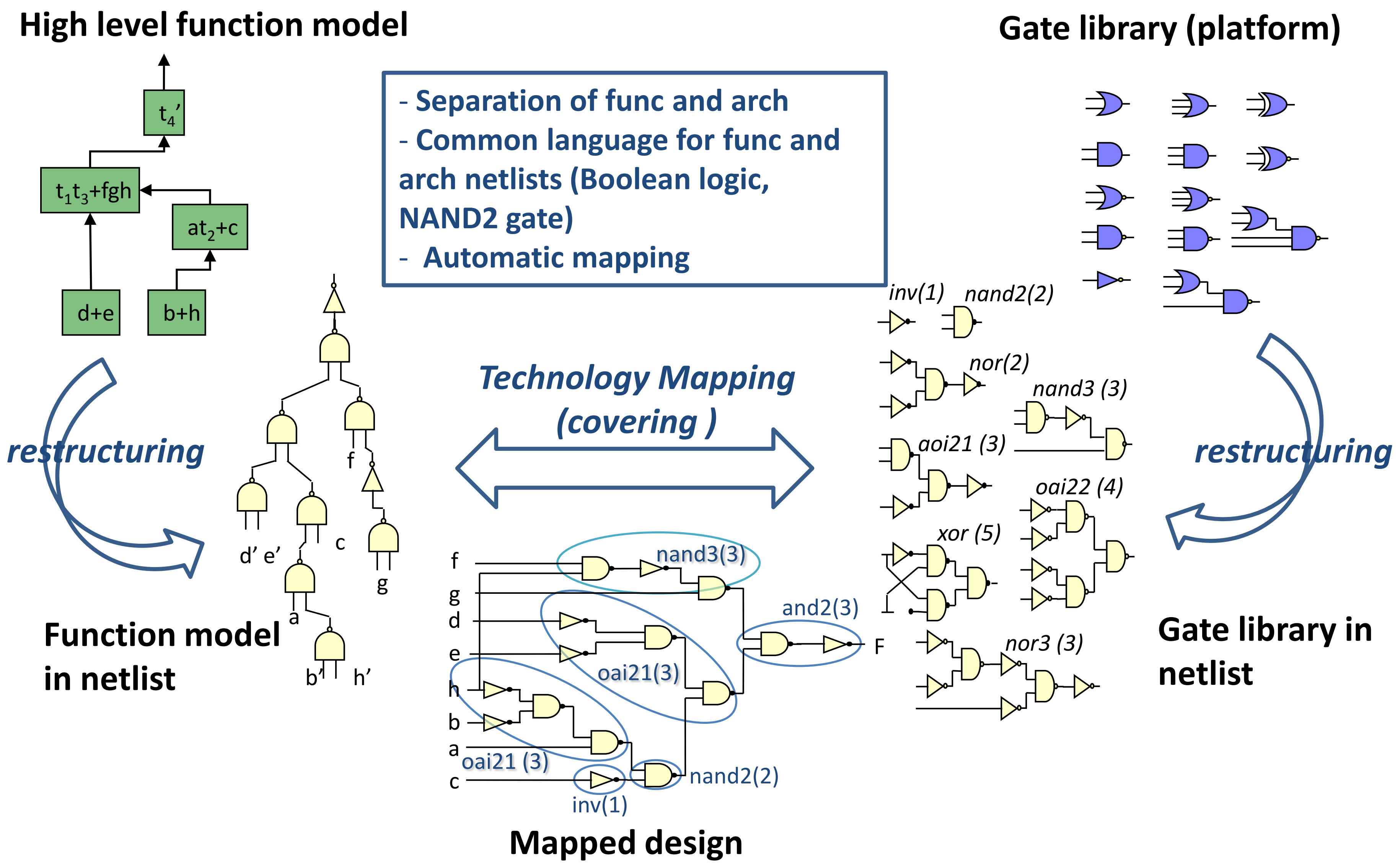


Platform: library of resources defining an abstraction layer with interfaces that allow legal connections

- **Resources do contain virtual components i.e., placeholders that will be customized in the implementation phase to meet constraints**
- **Very important resources are interconnections and communication protocols**

Learning from logic synthesis

- Separation of func and arch
- Common language for func and arch netlists (Boolean logic, NAND2 gate)
- Automatic mapping



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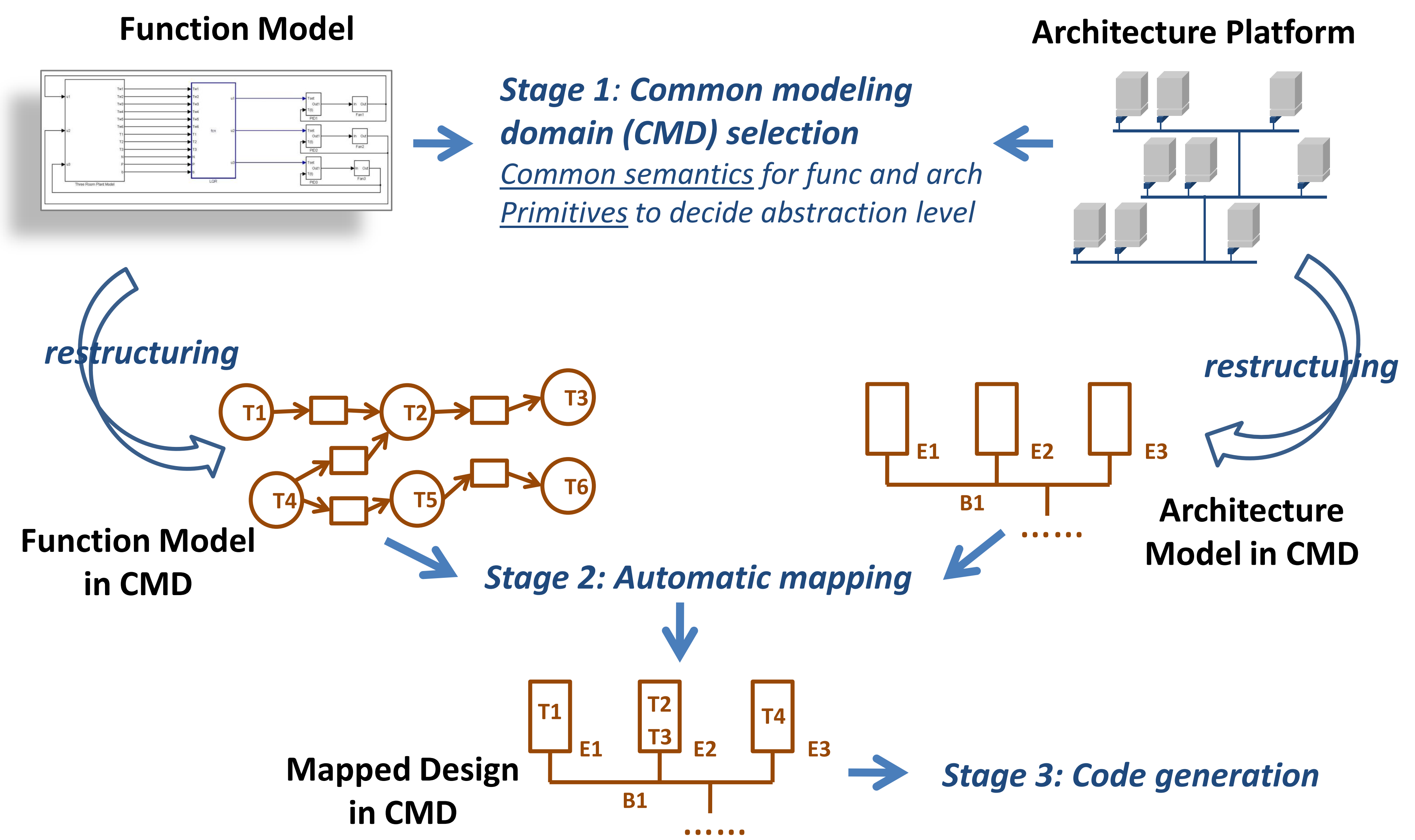
Our software synthesis flow



Challenges in the flow

- Stage 1: Common modeling domain selection
  - Various models of computation exist in system level.
  - Trade-off between expressiveness and ease of manipulation when selecting the <u>common semantics</u>.
  - Trade-off between granularity and optimality when selecting the <u>primitives</u>.
- Stage 2: Automatic mapping
  - Various constraints and objectives.
  - Domain-specific algorithms may be used albeit not necessary.
- Stage 3: Code generation
  - Communication interface synthesis maybe needed to guarantee correct semantics.

Modeling domain

- Semantic domain Q - *the language*
  - Formally defined as trace-based agent algebra [1].
  - $Q.D$: domain of agents - “building blocks”.
  - $Q.A$: master alphabet – “set of all signals between blocks”.
  - $Q.\alpha : Q.D \rightarrow 2^{Q.A}$, each agent has an alphabet – “each block has a set of signals”
  - Operators: renaming, projection and parallel composition – “rules to initialize and compose blocks”
- Primitives P – *abstraction level*
  - Primitives are a set of agents in a semantic domain, $P \subseteq Q.D$.
  - No agent in P can be constructed from other agents in P.
- Modeling domain $C_Q(P)$: all agents constructed from primitives P by applying operators in semantic domain Q.

[1] R. Passerone, *Semantic Foundations for Heterogeneous Systems. PhD* thesis, University of California, Berkeley, 2004.

Common modeling domain (CMD)

- A model is an agent in the modeling domain.
- Function model $f \in F$, architecture model $a \in A$.
- $B(s)$ denotes the behavior of model s.
- Modeling domain M is a common modeling domain between f and a if there exists $f' \in M$ and $a' \in M$ s.t. $B(f') \subseteq B(f)$ and $B(a') \subseteq B(a)$.

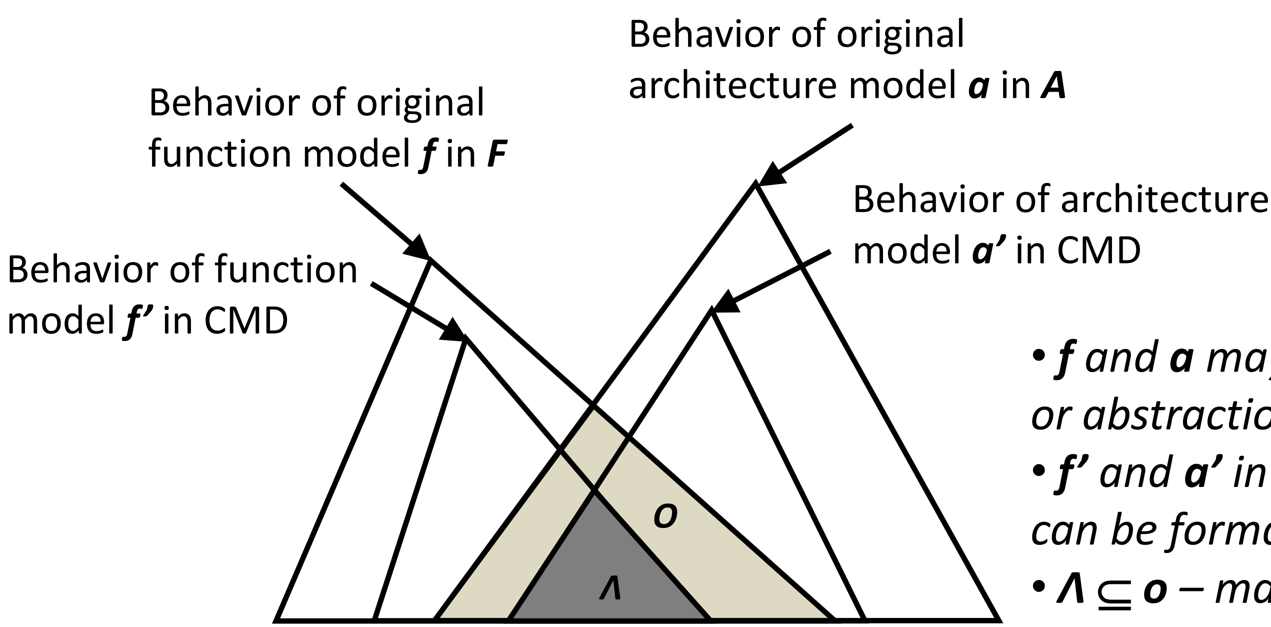
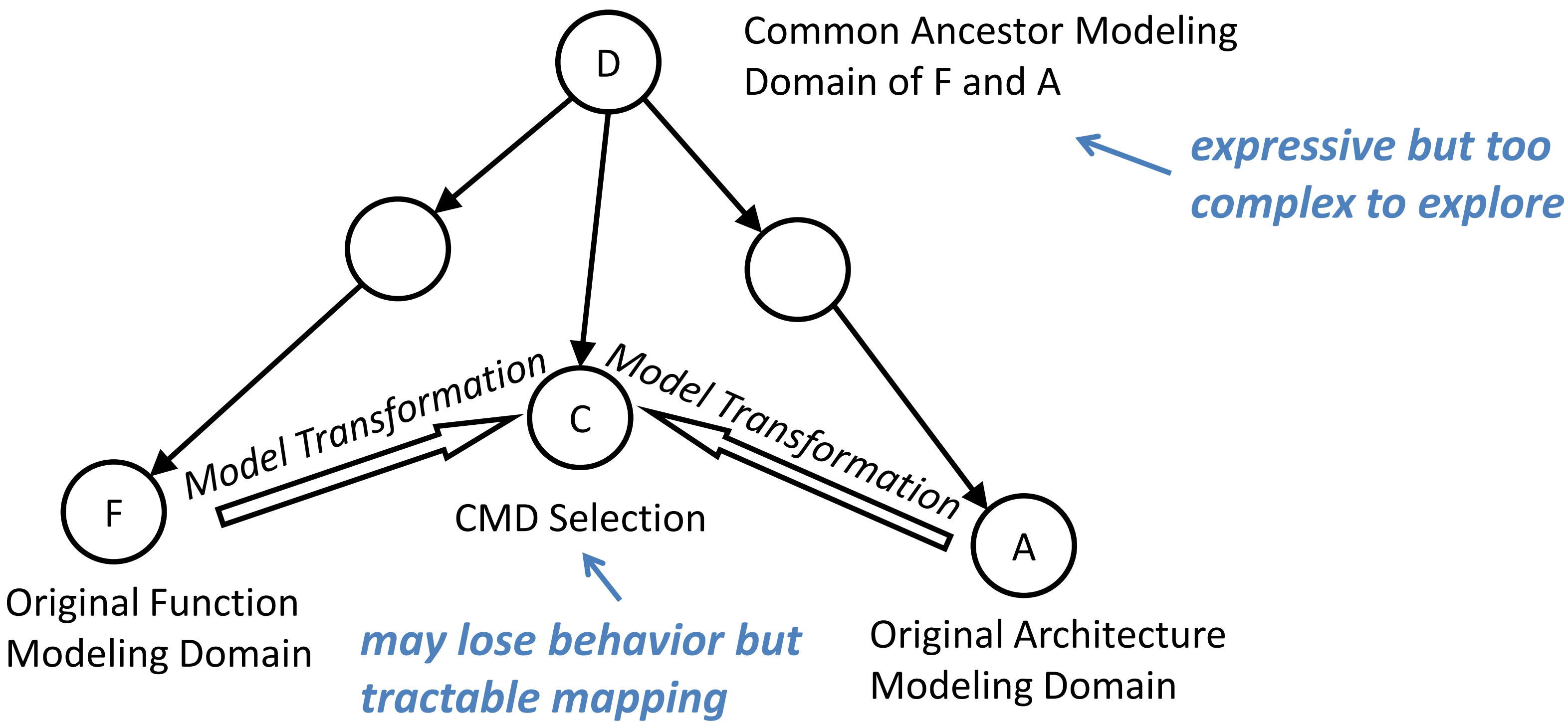


Illustration of mapping space in CMD

- ***f*** *and* ***a*** *may have different semantics or abstraction level – hard to explore* ***o****.*
- ***f'*** *and* ***a'*** *in CMD – mapping space* ***Λ*** *can be formally explored.*
- $\boldsymbol{\Lambda} \subseteq \boldsymbol{o}$ *– mapped behavior is* ***legal****.*

CMD selection

- Ancestor-child relation between modeling domains.
  - Define $\Phi(M) = \{B(s) \mid s \in C_Q(P)\}$ – set of all agent behavior.
  - $M_1 = C_{Q_1}(P_1)$ is the ancestor of $M_2 = C_{Q_2}(P_2)$ iff $\Phi(M_2) \subseteq \Phi(M_1)$.
- Search CMDs on modeling domain relation graph (directed edges representing ancestor-child relation).



CMD selection contd.

- Two design aspects when selecting CMD $C = C_Q(P)$
  - Semantics – decided by semantic domain *Q*
    - Expressiveness vs. analyzability, e.g. dataflow vs. static dataflow.
    - May first choose semantic domain for common ancestor domain *D*, then refine it in *C.*
  - Abstraction level – depends on primitives *P*
    - Explore different abstraction level by choosing different primitives.
    - Carried out when selecting *C* as child domain of *D.*
  - For both, it is a trade-off between the size of mapping space and complexity.

Covering problem after CMD selection

- Symbols:
  - Function primitive instances : $F = (f_1, f_2, ..., f_n)$
  - Architecture primitive instances : $A = (a_1, a_2, ..., a_m)$
  - Mapping decision variables : d_{f_i, a_j}
  - Architecture selection variables: s_{a_j}
  - Quantities (power, area, bandwidth…): $Q_{f_i, a_j, t}$ $Q_{a_j, t}$
- General covering formulation

Function covering constraints

$$\forall f_i \in \mathcal{F}, \quad \sum_{a_j \in \mathcal{A}_{f_i}} d_{f_i,a_j} = 1$$

$$\forall f_i \in \mathcal{F}, a_j \notin \mathcal{A}_{f_i}, \quad d_{f_i,a_j} = 0$$

Architecture selection constraints

$$\forall a_j \in \mathcal{A}, \quad \sum_{f_i \in \mathcal{F}} d_{f_i,a_j} \geq s_{a_j}$$

$$\forall f_i \in \mathcal{F}, a_j \in \mathcal{A}, \quad d_{f_i,a_j} \leq s_{a_j}$$

Domain specific. Determines complexity!

Quantity constraints

$$H_{t,l}(\{d_{f_i,a_j}\}, \{Q_{f_i,a_j,t}\}, \{s_{a_j}\}, \{Q_{a_j,t}\}) \leq 0$$

Objective functions

$$\min \ G_t(\{d_{f_i,a_j}\}, \{Q_{f_i,a_j,t}\}, \{s_{a_j}\}, \{Q_{a_j,t}\})$$

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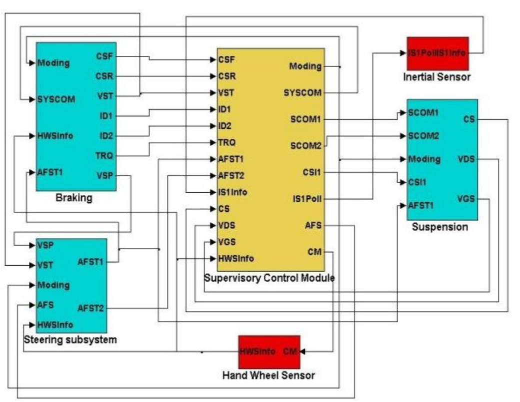
Case study: active safety vehicle

- Functional correctness and cost-efficiency are both important for active safety applications.
- Function and architecture mismatch.

Function model

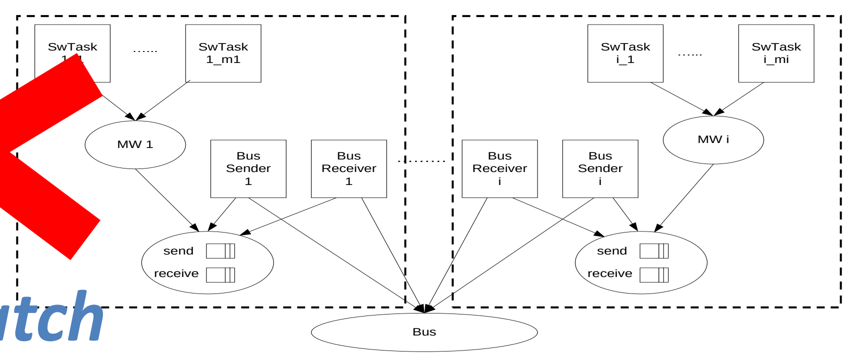
- synchronous model.
- no message loss or duplication.



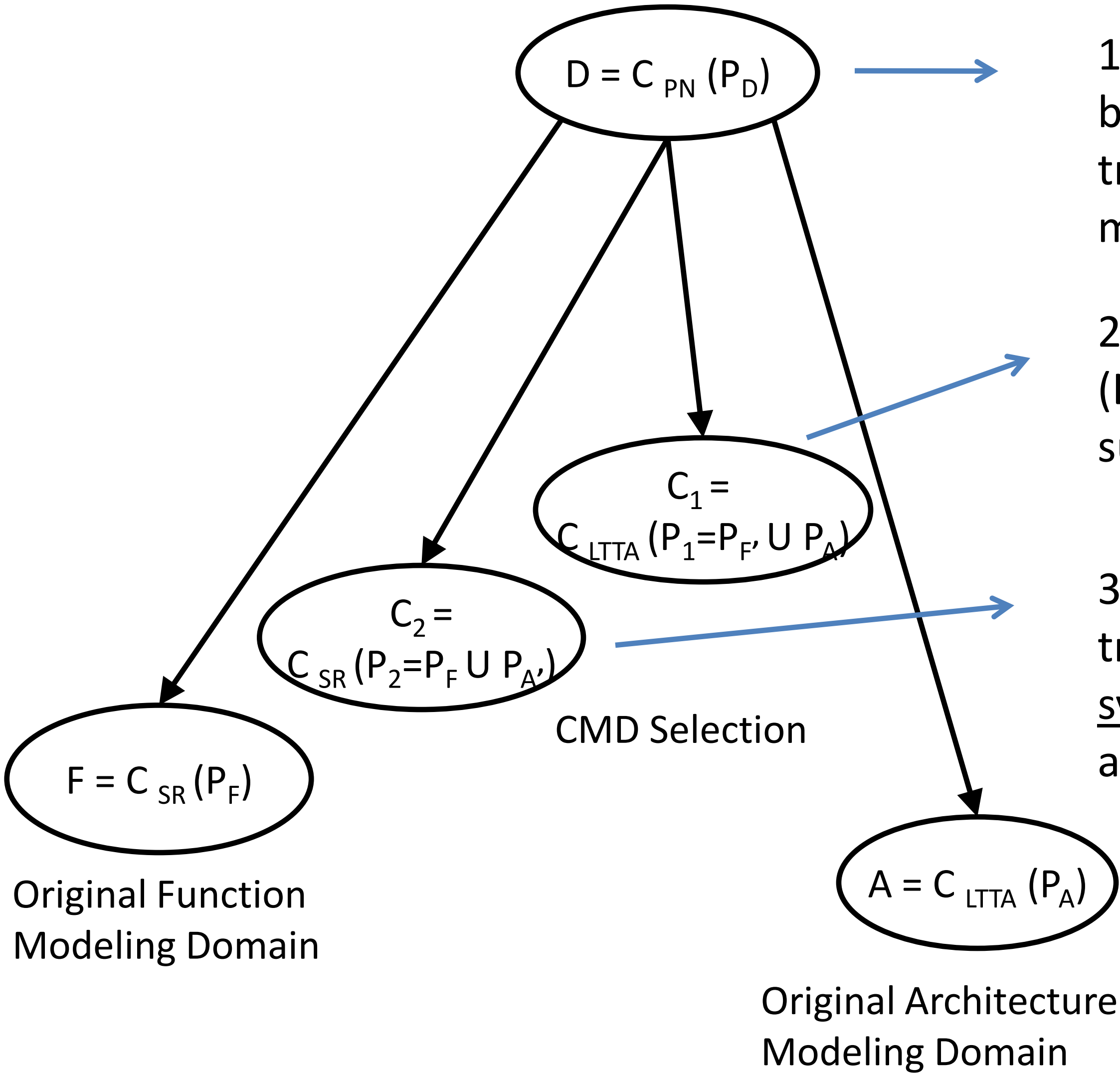
mismatch

Architecture platform

- clock drift between distributed ECUs, asynchronous communication.
- data loss and duplication exist.



Stage 1: CMD selection – common semantics



1. Process Networks (PN): expressive but high modeling complexity. Need transformation of both func and arch models.

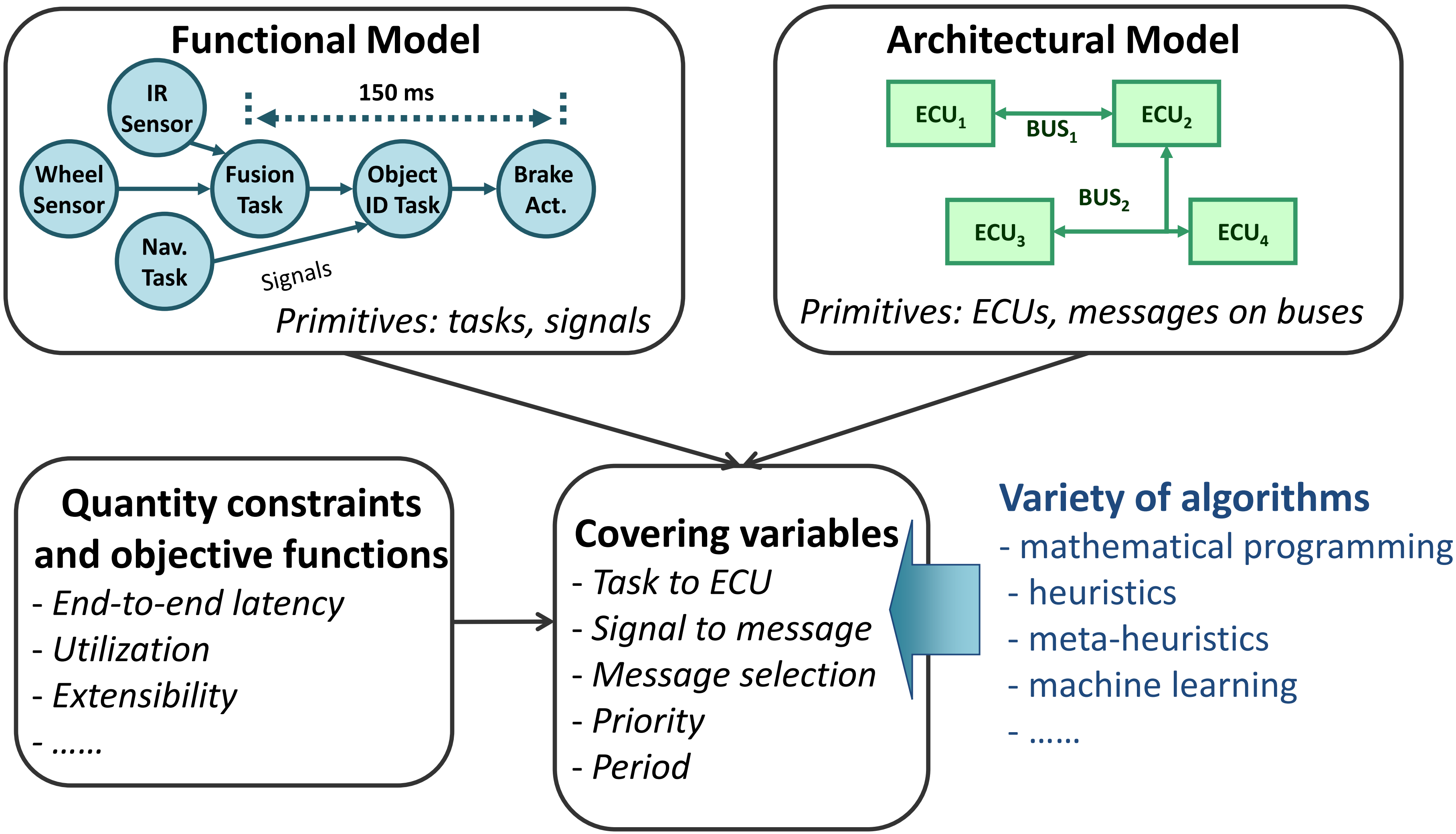
2. Loosely time triggered architecture (LTTA): transformation of func model to support asynchronous communication.

Chosen in this case study

3. Synchronous reactive (SR): transformation of the arch to support synchronous communication, by applying following protocols.

- Clock synchronization.
- Constraints on task periods.

Stage 2: covering problem



Stage 2: covering problem contd.

- Worst case analysis for CAN systems with periodic tasks and messages.
- A complete formulation with all design variables does not scale for industrial size problems.
- We start with tackling following sub-problems.

Problems	Period Synthesis [1]	Allocation & Priority Synthesis [2]	Extensibility Optimization [3, 4]
Variables	Period	Allocation Priority	Allocation Priority
Objective	Latency	Latency	Extensibility
Approach	Geometric programming (GP)	Mixed integer linear programming (MILP)	Multi-step Heuristic

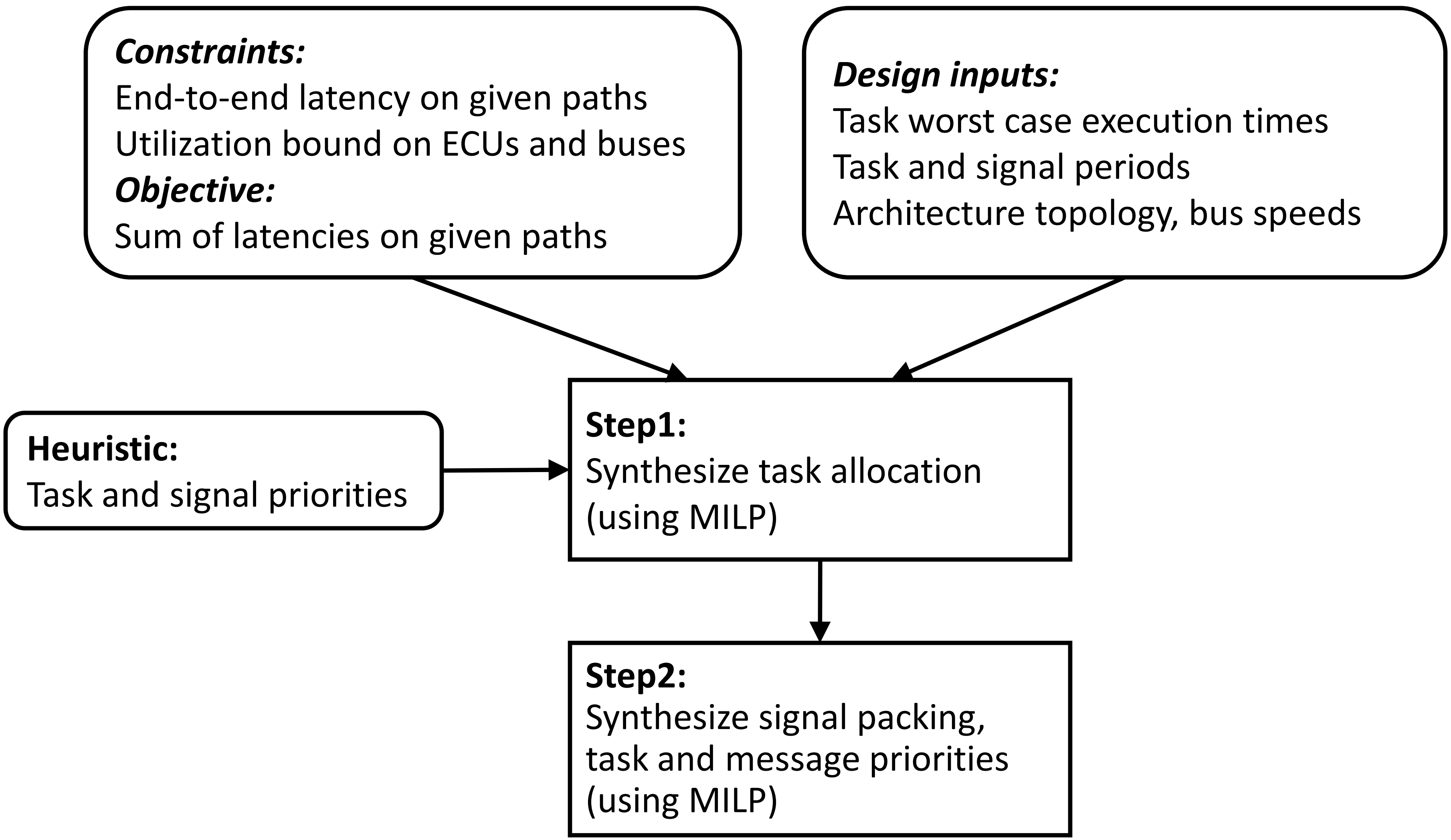
[1] "Period Optimization for Hard Real-time Distributed Automotive Systems", 44th DAC, 2007.

[2] "Definition of Task Allocation and Priority Assignment in Hard Real-Time Distributed Systems", 28th RTSS, 2007.

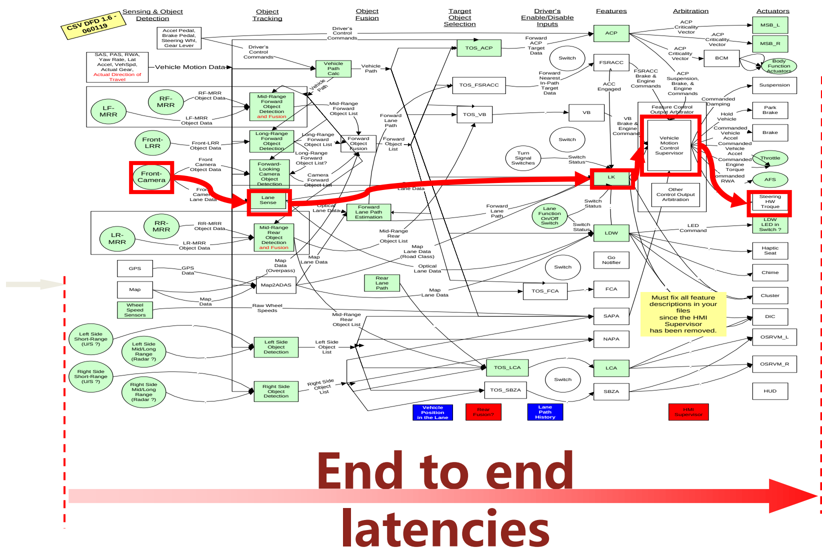
[3] "Optimizing Extensibility in Hard Real-time Distributed Systems", 15th RTAS, 2009.

[4] "Optimizing the Software Architecture for Extensibility in Hard Real-Time Distributed Systems", TII, 2010.

Allocation & priority synthesis (MILP based)



Allocation & priority synthesis results



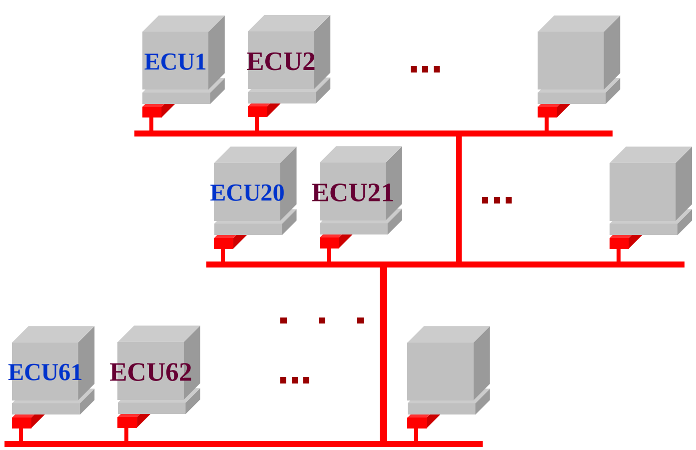
Function Model

- 41 Tasks
- 83 Signals
- 171 paths

After mapping

- ***Meet all requirements***
- ***Total latency from 36486ms in manual design to 12900ms***

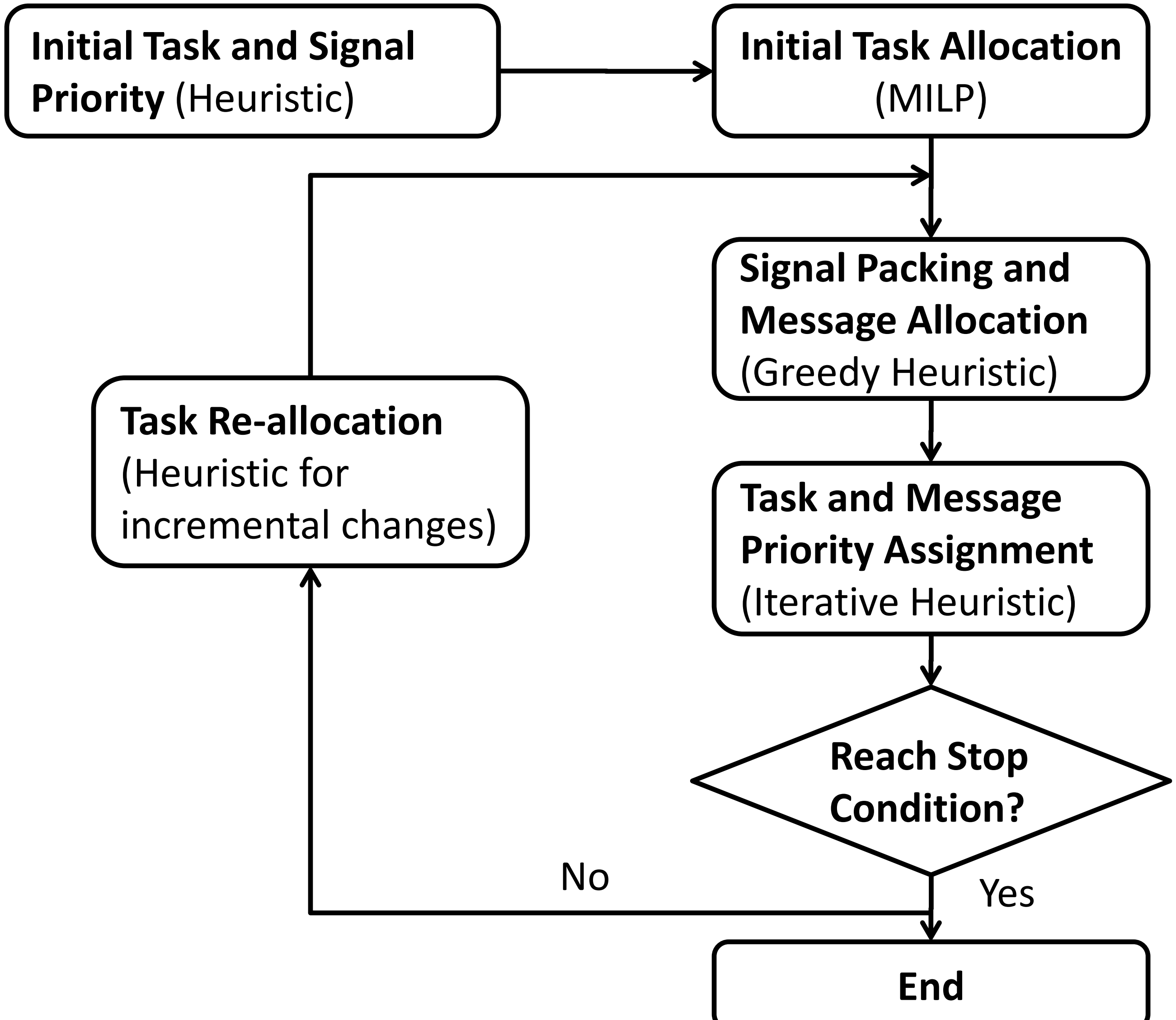
Mapping



Architecture platform

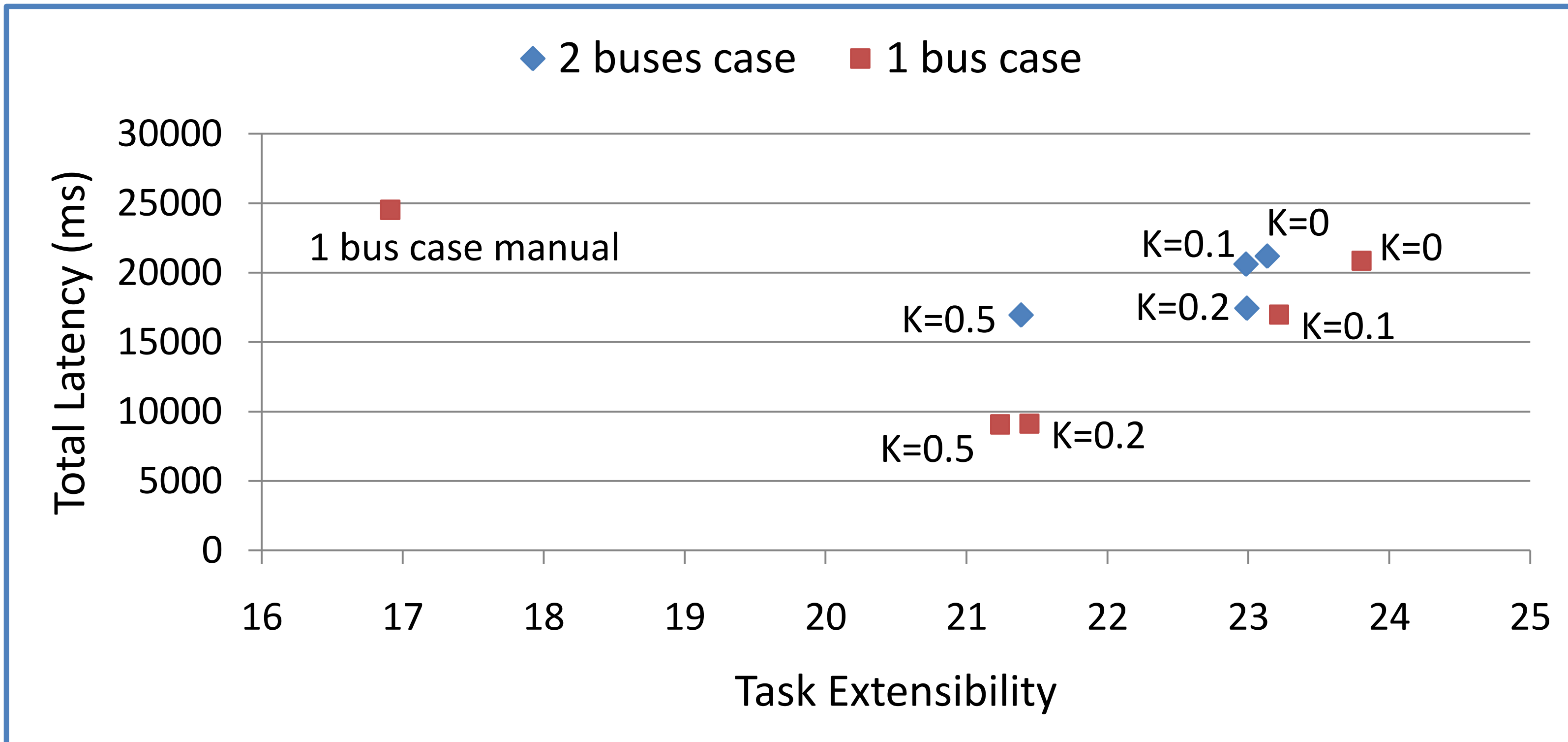
- 9 ECUs
- single bus

Extensibility optimization (MILP and heuristic)



Extensibility optimization results

- Same active safety vehicle as in allocation and priority synthesis.
- Single-bus and dual-bus options.
- Parameter *K* to trade off between extensibility and latency.
- Compared with a simulated annealing algorithm: maximum extensibility within 0.3%, runtime 0.5 hour vs. 12 hours.



Case studies in other domains

- Building automation domain [1]
  - Similar semantics as in automotive – synchronous function model and LTTA architecture platform.
  - Also choose SR as the common semantics, however additional timing constraints are added to the architecture for preserving synchronism, as we consider the physical interaction with environment.
  - Mapping leverages COSI for communication network synthesis.
- Multimedia domain [2]
  - JPEG encoder application. Intel MXP architecture platform.
  - Semantics for both function and architecture are dataflow.
  - Challenge is to choose the proper abstraction level. Different levels are explored and compared through choices of primitives.

[1] “A Design Flow for Building Automation and Control Systems”, 31st RTSS, 2010.
[2] “JPEG Encoding on the Intel MXP5800: A Platform-Based Design Case Study”, ESTIMedia’05, 2005.

Concluding remarks

- Software (and hardware) synthesis based on a formal mapping procedure
  - Formally determines the semantics and abstraction level of the design by choosing a common modeling domain.
  - Automatic and optimal mapping algorithms.
  - *Generality* – applied to various domains with different models of computation as well as different implementation platforms. Domain-specific mapping algorithms may be leveraged in the framework.
  - *Optimality* – trade-off between complexity and mapping space through the selection of CMD.
  - *Reusability* – common semantic selection requires designers' expertise. However proper selection is typically general for particular domains.