A General Synthesis Approach for Embedded Systems Design with Applications to Multi-media and Automotive Designs

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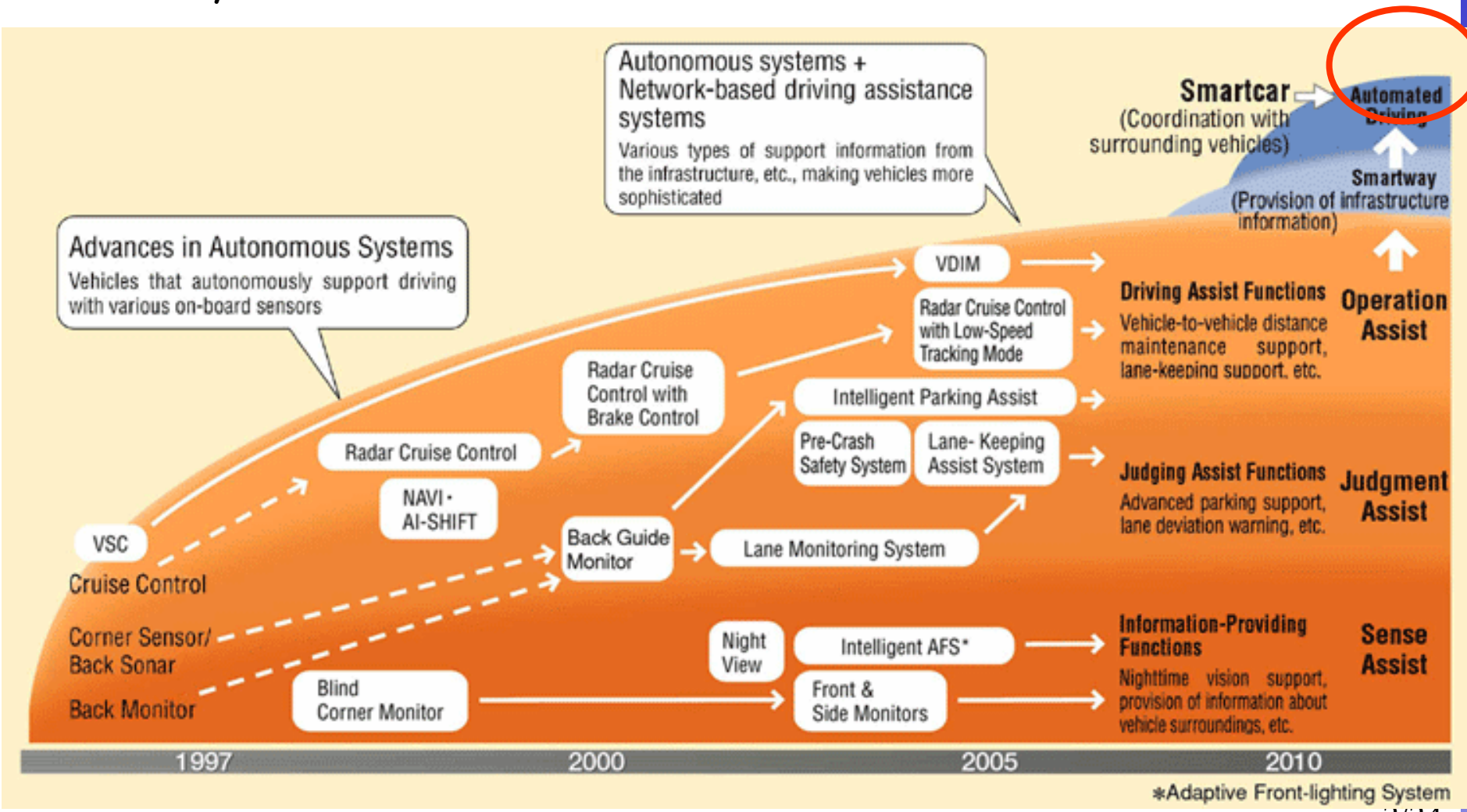
(Qi Zhu and Abhijit Davare)

Outline

- Design Trends and Challenges
- Semantic-Driven Synthesis Flow
  - Common Modeling Domain
  - Automatic Synthesis
- Validating the Design Flow
  - Automotive Stability Control
  - Image Processing
- Future Work

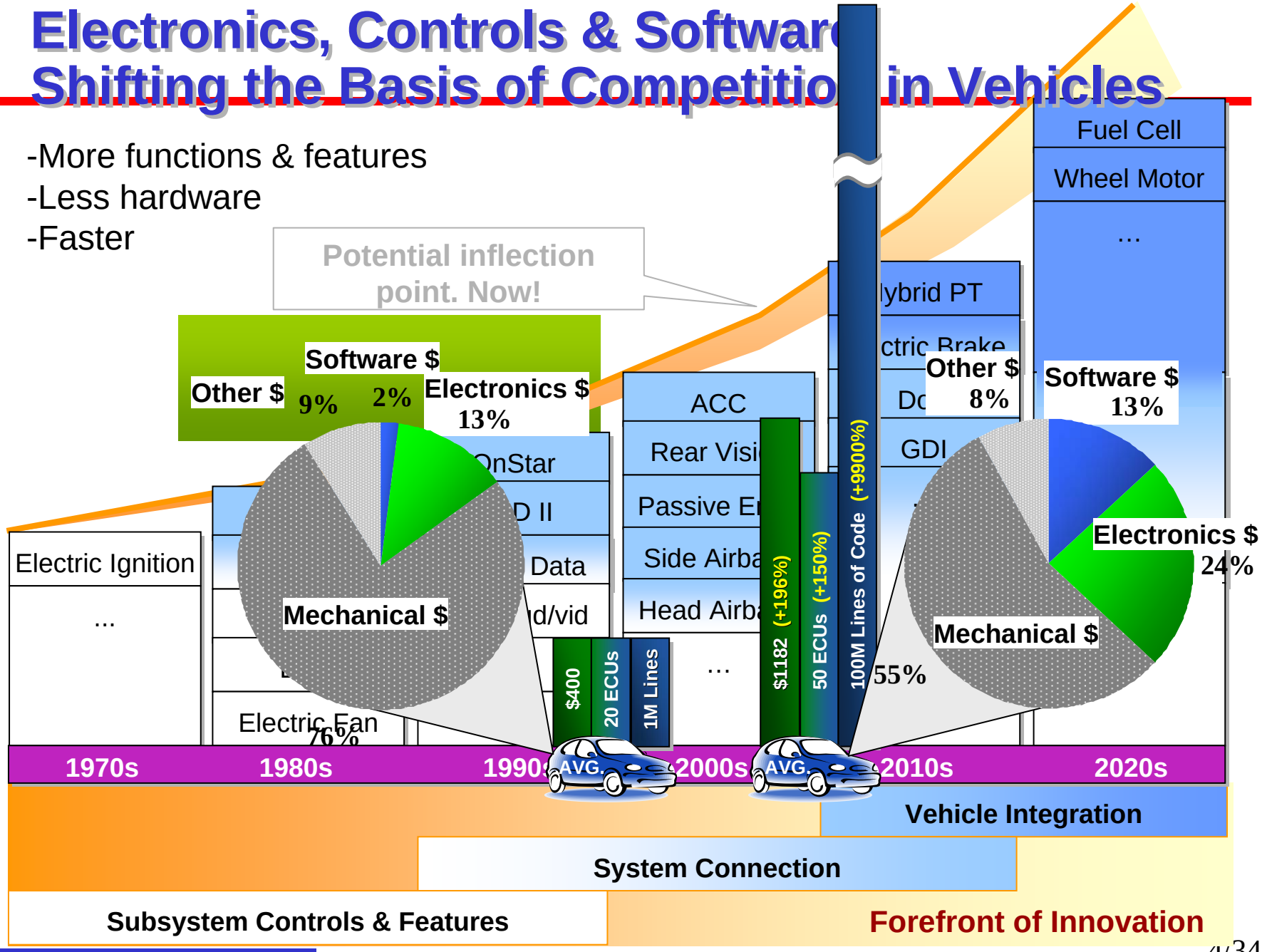
Toyota Autonomous Vehicle Technology Roadmap

Source: Toyota Web site



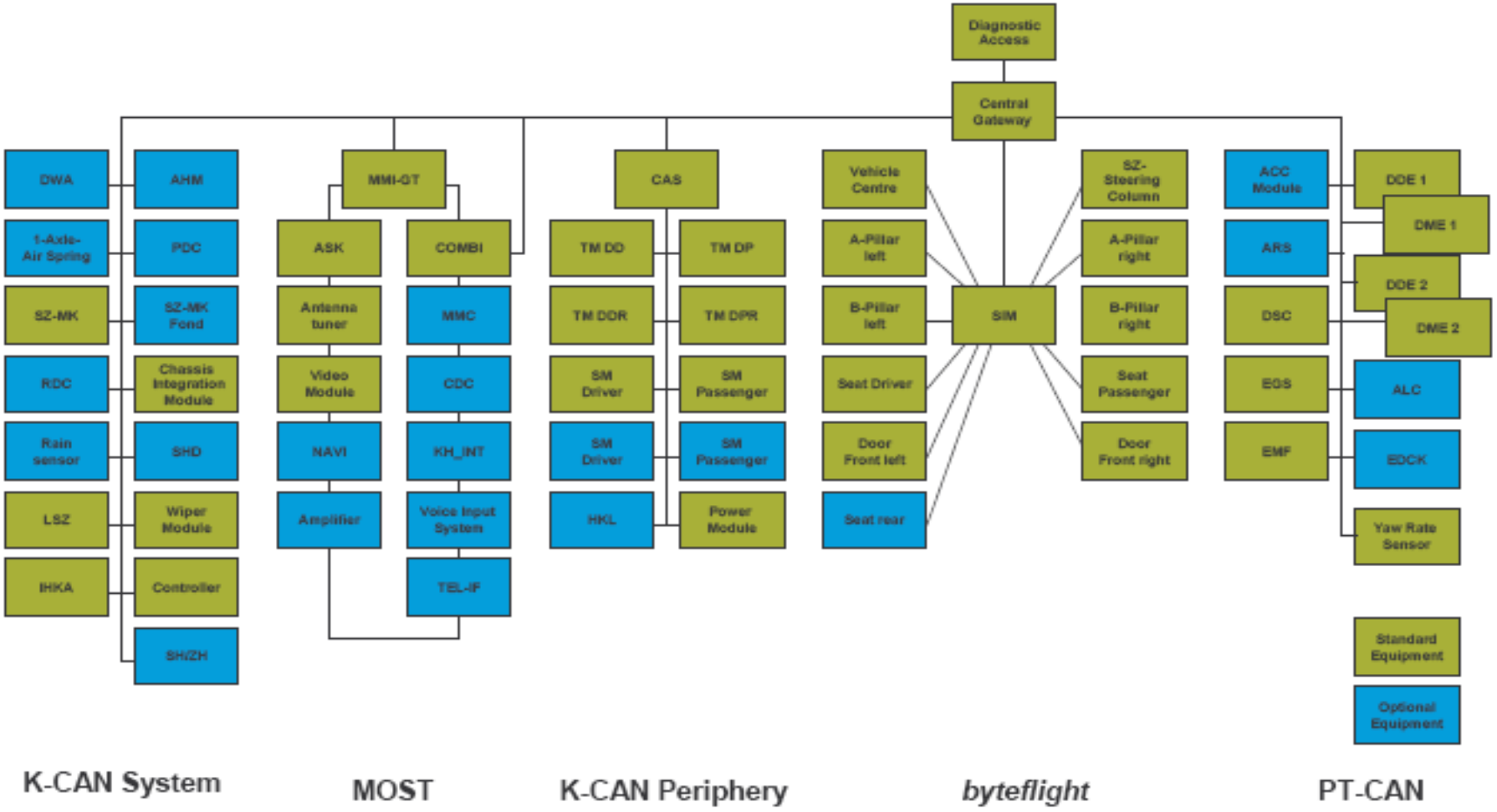
Electronics, Controls & Software Shifting the Basis of Competition in Vehicles

-More functions & features
-Less hardware
-Faster



Source: Matt Tsien, GM

A Typical Car Architecture (BMW)



Design Trends

- Time to market
- Reliability
- Flexibility

Complexity of embedded systems

- ***Design reuse***
- ***Correct-by-construction***

Separation of concerns

Functionality

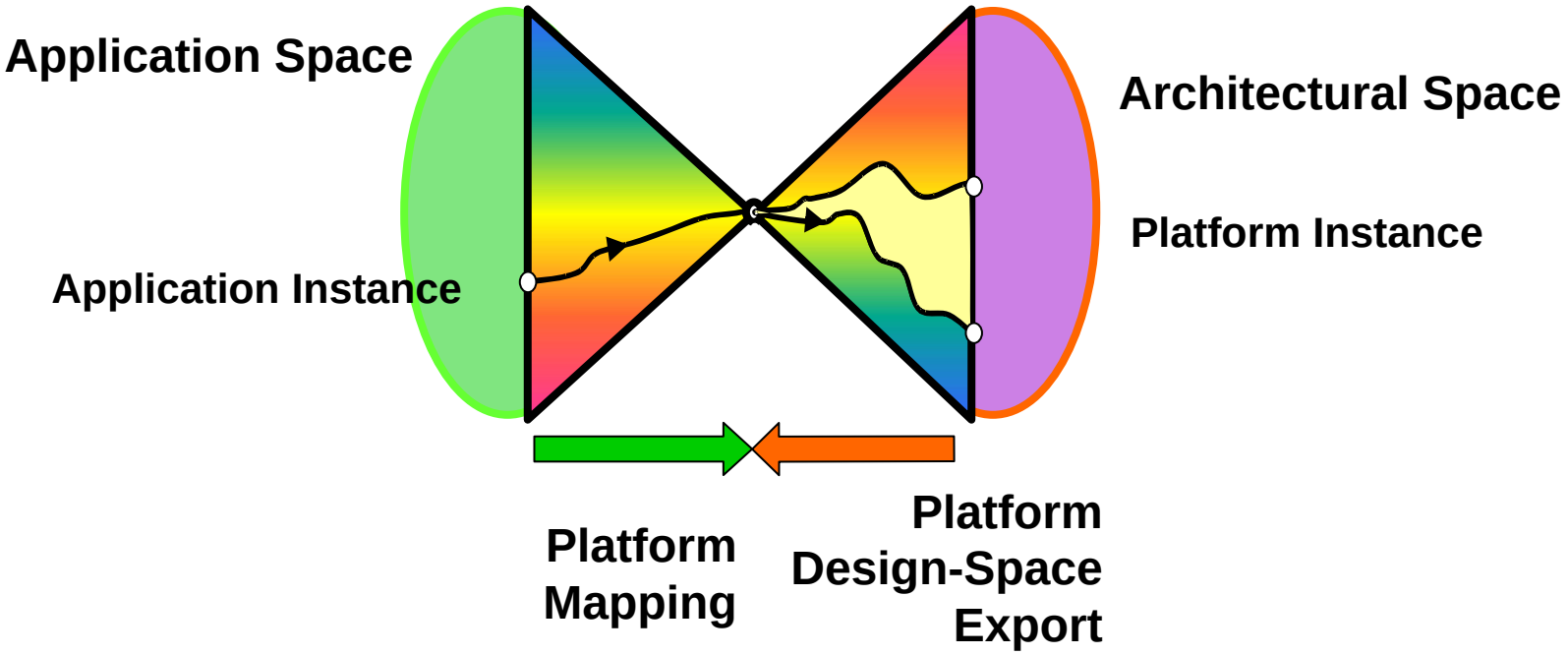
MP3, MPEG-4, Wi-Fi, BT, GPS …

Mapping ?

Architecture

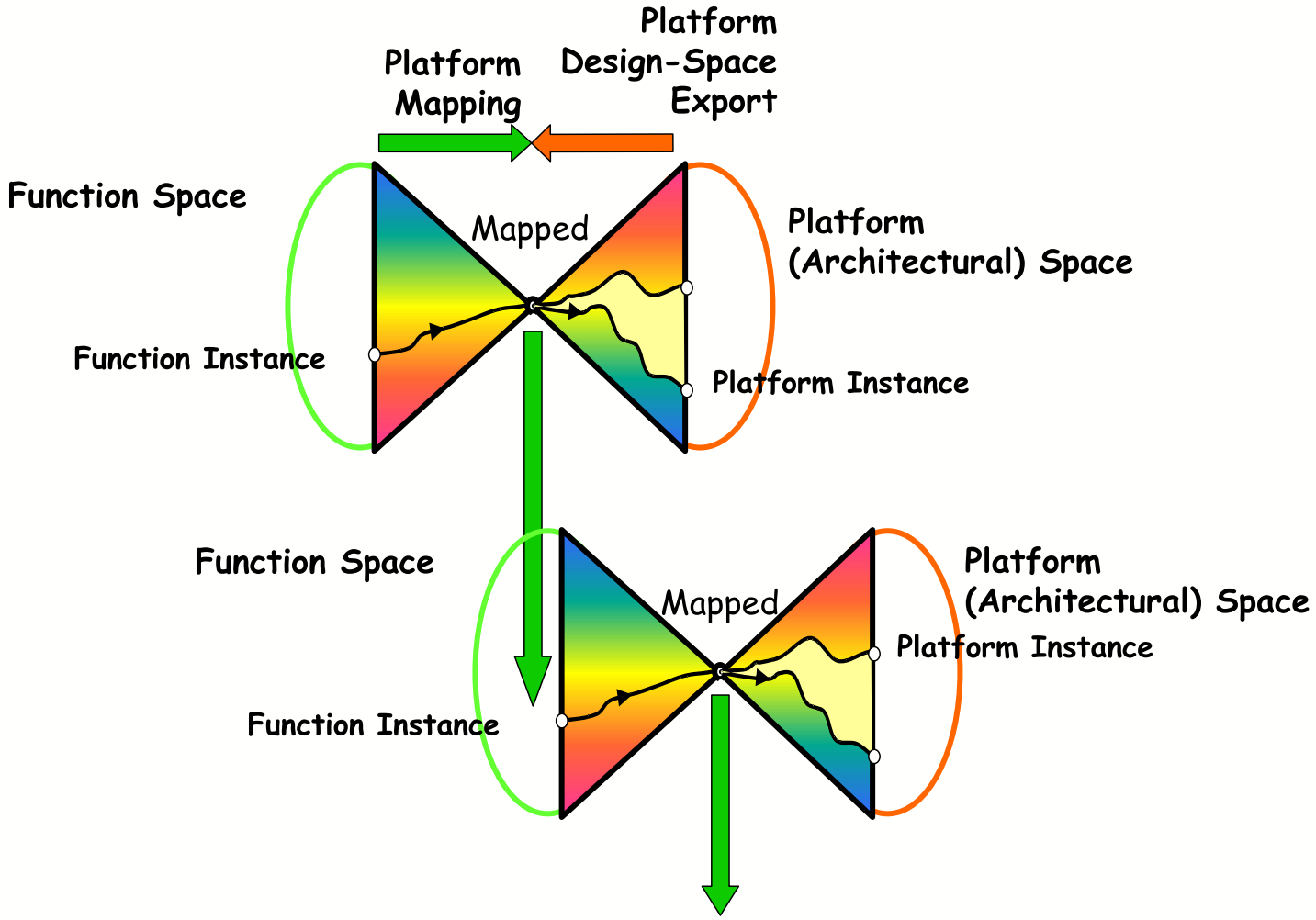
Cell, MXP series, IXP series, Nexperia …

Platform-based Design

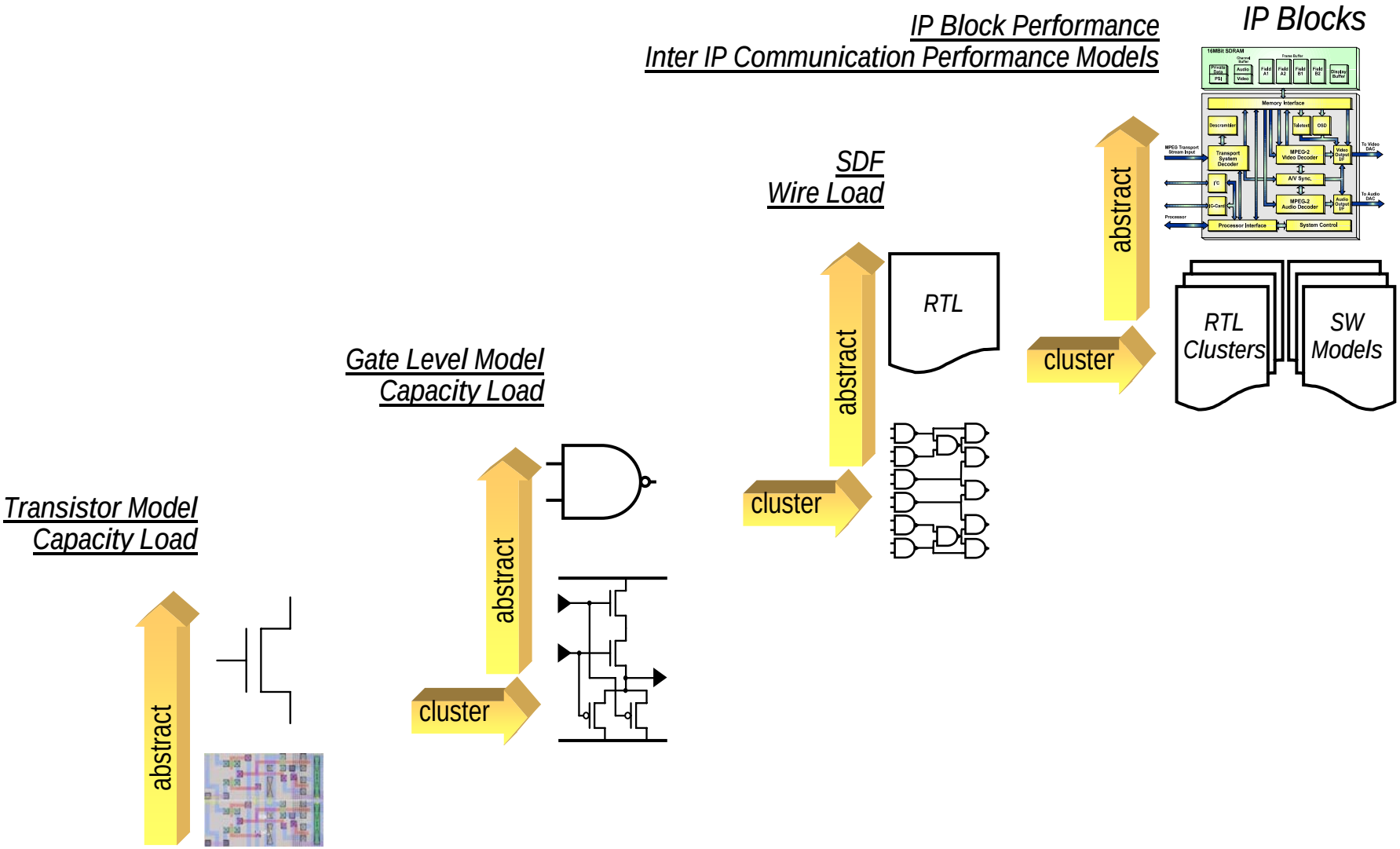


- Platform: library of resources defining an abstraction layer
  - Resources do contain virtual components i.e., place holders that will be customized in the implementation phase to meet constraints
  - Very important resources are interconnections and communication protocols

Fractal Nature of Design

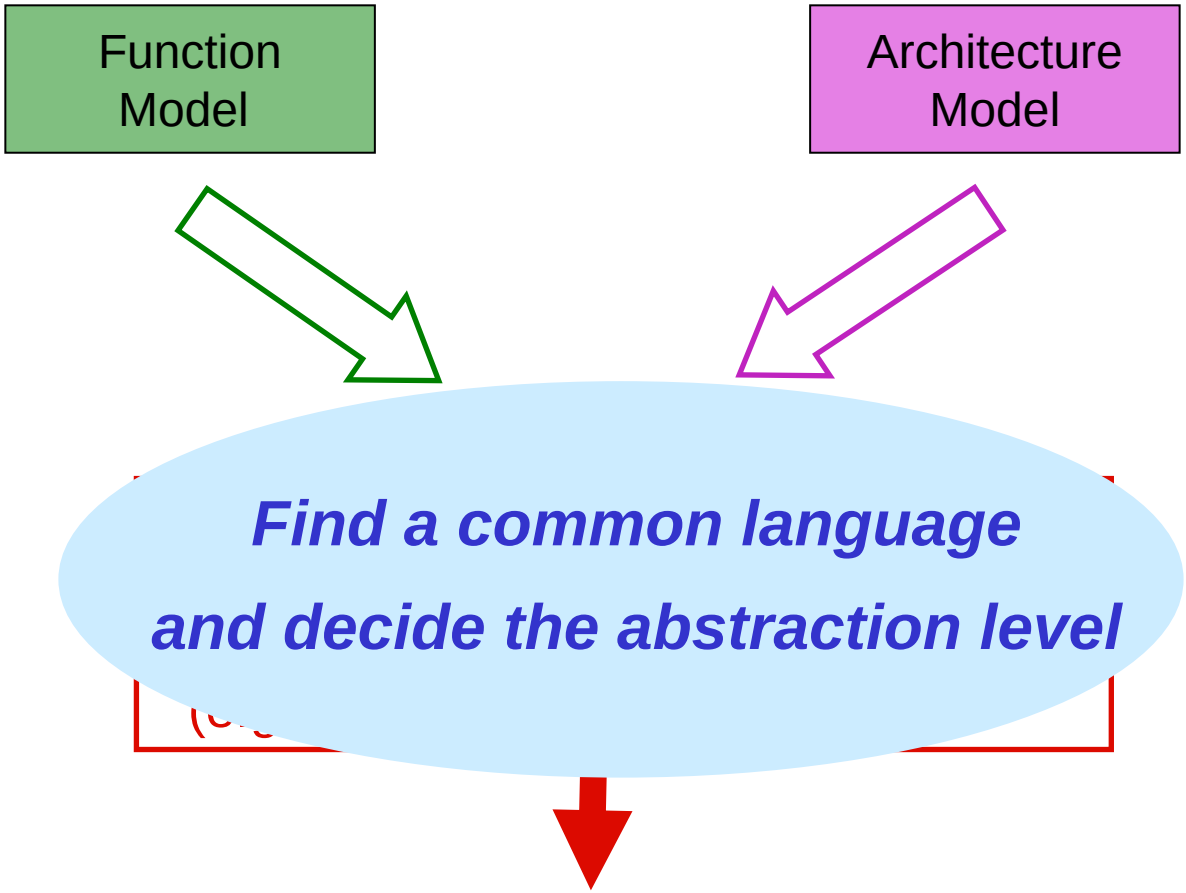


The next level of Abstraction …



Challenge

Functionality and Architecture are modeled separately



Mapping could be automatic, manual, by construction

Mapping should be automatic, correct-by-construction

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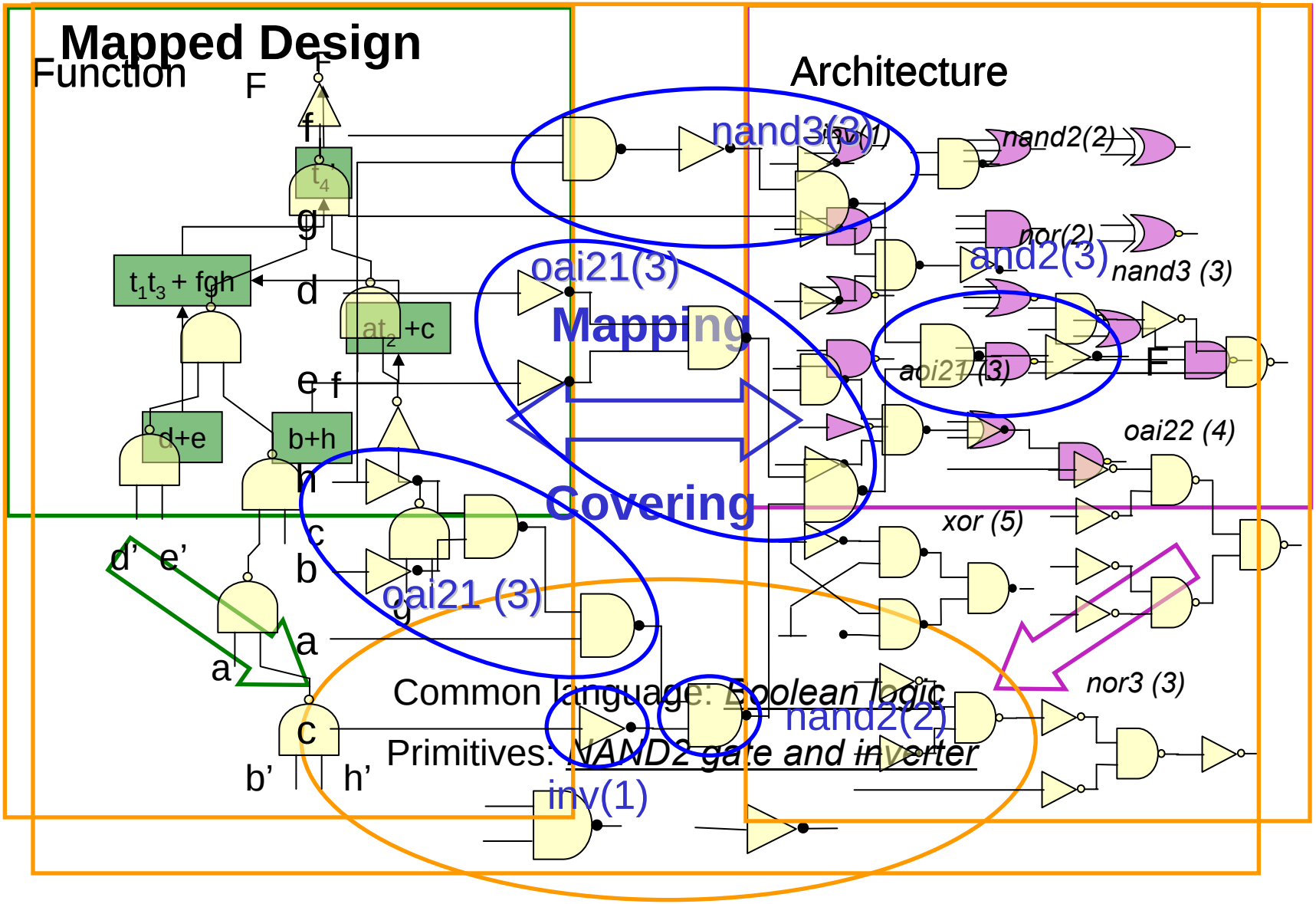
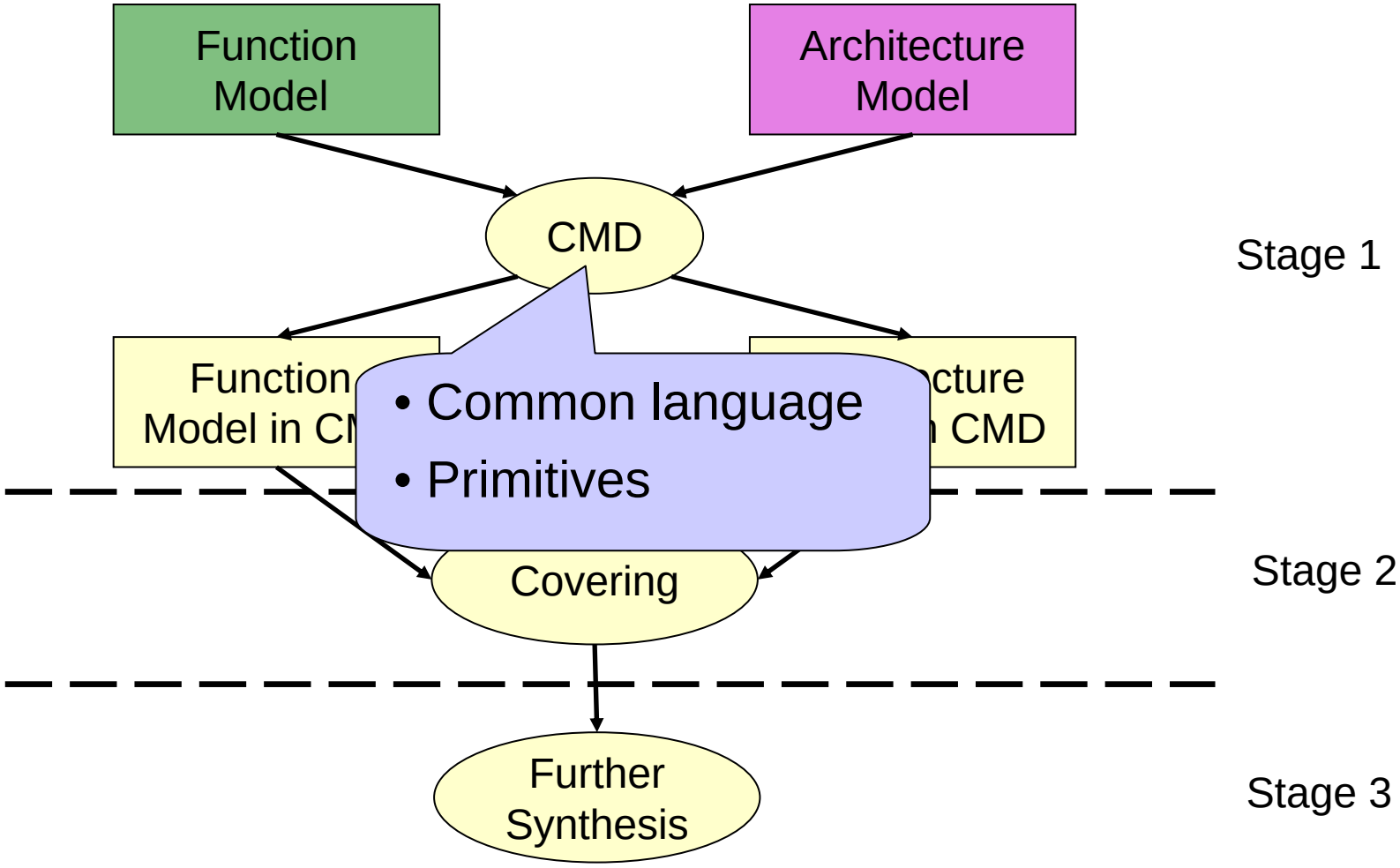
Technology Mapping



Synthesis Flow

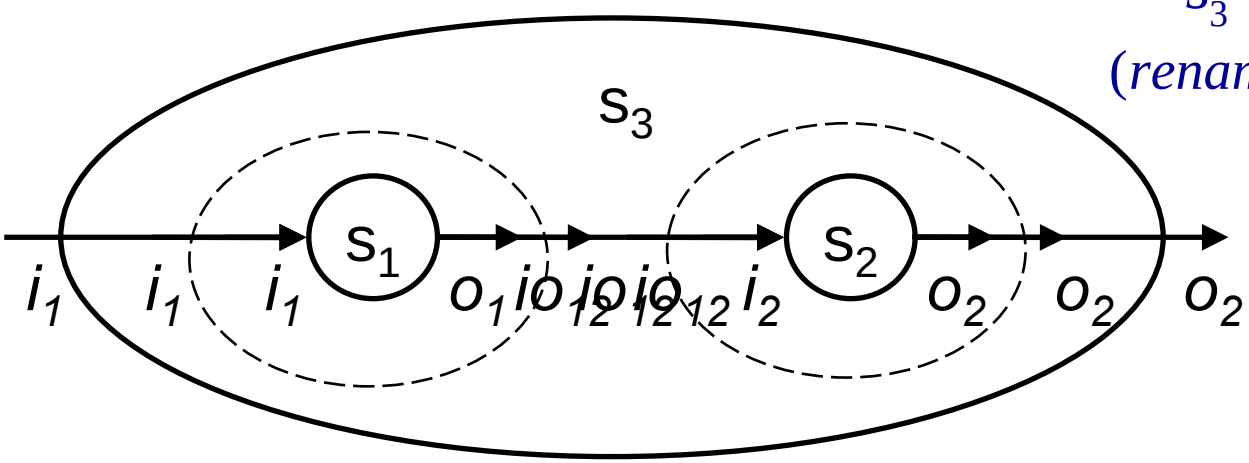


Modeling Domain – Semantic Domain

Modeling domain is based on semantic domain and primitives

- *Q*: semantic domain - language
  (trace-based agent algebra [R. Passerone, PhD thesis])
  - *Q.D*: domain of agents – "building blocks"
  - *Q.A*: master alphabet – "all signals between blocks"
  - *Q.α : Q.D -> $2^{Q.A}$*, each agent has an alphabet which is a subset of *Q.A* – "each block has a set of signals"
  - Operators: renaming, projection and parallel composition – "rules to initialize and compose agents"

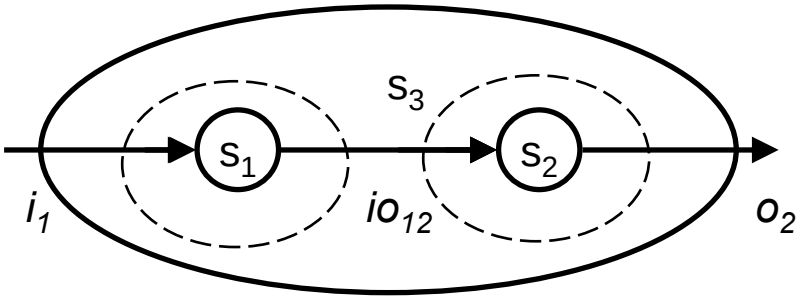
$$s_3 = proj(\{i_1, o_2\})$$
$$(rename(r)(s_1) \,||\, rename(r)(s_2))$$



PN semantics

Modeling Domain – Primitives

- New agents can be constructed by applying a finite number of operators in sequence on existing agents.
- Agent Closure $C_Q(S)$ contains all the agents that can be constructed from a set of agents S by applying operators in semantic domain Q.
- Primitives P – abstraction level
  - Primitives are agents, $P \subseteq Q.D$.
  - No agent in P can be constructed from other agents in P, i.e., $\forall p \in P$, there exists no $P' \subseteq P \setminus \{p\}$ s.t. $p \in C_Q(P')$.
  - $\{s_1, s_2\}$ is a set of primitives in *PN* semantics, $\{s_1, s_2, s_3\}$ is not.



Modeling Domain

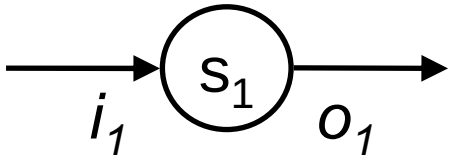
- Modeling domain $M = C_Q(P)$ is the agent closure of a set of primitives P in semantic domain Q.
  - Contains all the agents that can be constructed from P.

    E.g., $C_{PN}(\{s_1, s_2\})$ contains all the agents that can be constructed from $\{s_1, s_2\}$ by applying operators in PN semantics.
  - Semantic domain Q provides a language for modeling.
  - Primitive P defines a sub-space of the entire modeling space of Q. Abstraction level can be explored by choosing different primitives.

- *What is the relation between different modeling domains?*
- *What is common modeling domain?*

Relation between Modeling Domains

- Behaviors
  - Γ: $2^{Q.A}$ -> 2^{T}, each alphabet is associated with a set of traces over trace domain T.
  - Each agent s has a set of traces $\Gamma(Q.\alpha(s))$, which are called <u>behaviors</u>, denoted as $B(s)$.

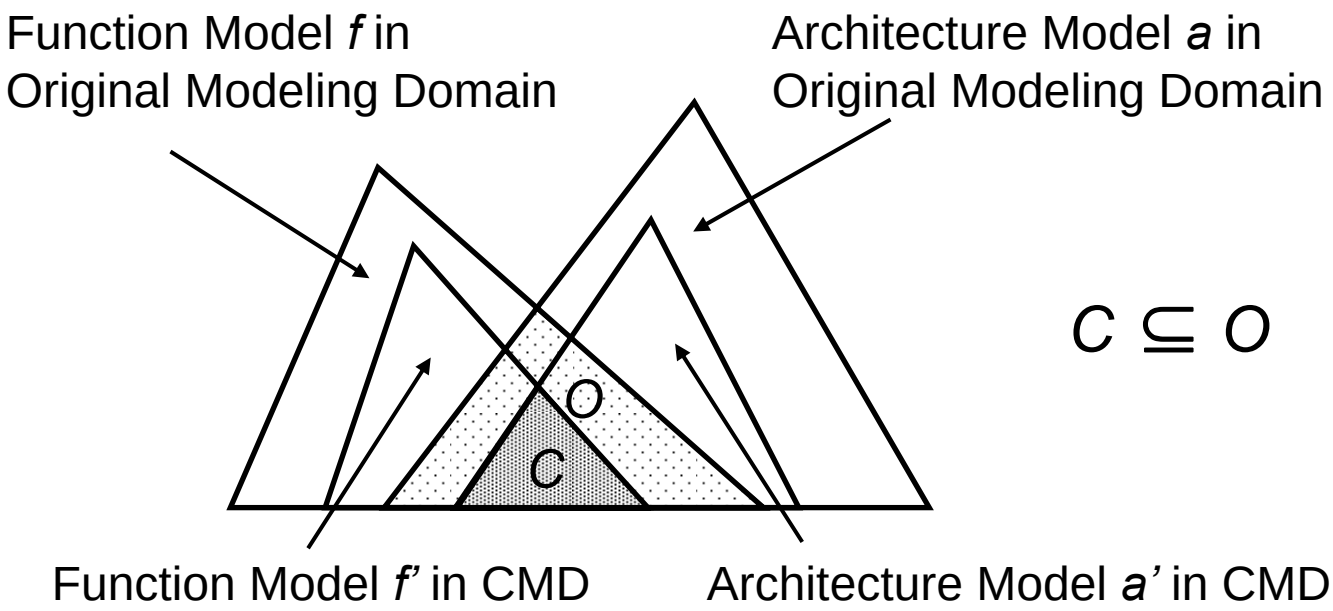


$$B(s_1) = \Gamma(Q.\alpha(s_1)) = (i_1 \rightarrow V^{\infty}) \times (o_1 \rightarrow V^{\infty})$$

- Ancestor-Child relation between modeling domains
  - $\Phi(M) = \{B(s) \mid s \in C_Q(P)\}$.
  - $M_1 = C_{Q_1}(P_1)$ is the ancestor of $M_2 = C_{Q_2}(P_2)$ if $\Phi(M_2) \subseteq \Phi(M_1)$, denoted as $M_2 \leq M_1$.
  - Example: $C_{PN}(\{s_3\}) \leq C_{PN}(\{s_1, s_2\})$
  - Ancestor – more expressive, higher modeling complexity
    Child – more specific, lower modeling complexity

Common Modeling Domain

- A model is an agent in the modeling domain.
- A modeling domain *M* is called common modeling domain between function model *f* and architecture model *a* if there exists $f' \in M$ and $a' \in M$ such that $B(f') \subseteq B(f)$ and $B(a') \subseteq B(a)$.

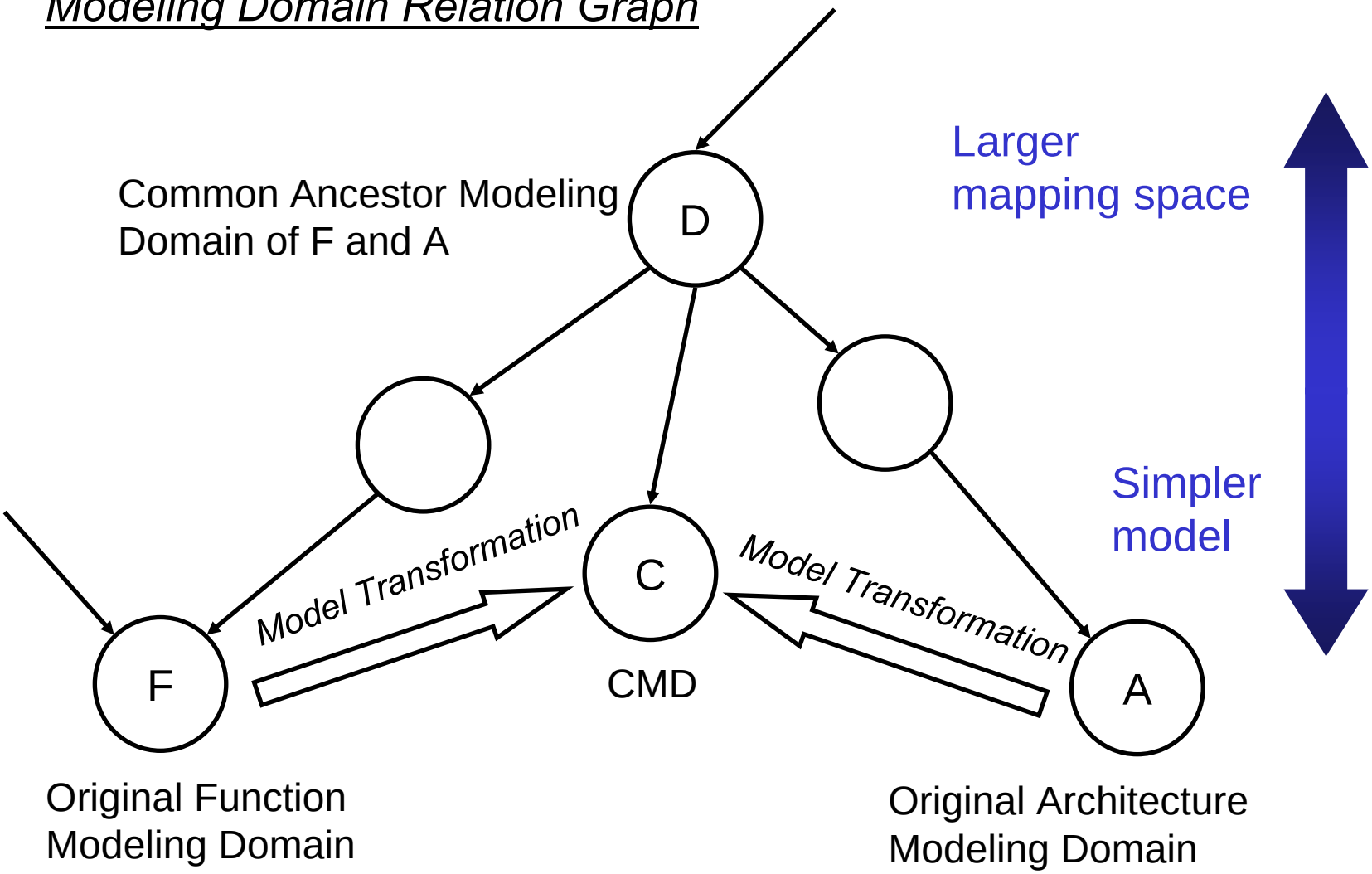


$C \subseteq O$

CMD Selection

Search for CMDs on

<u>Modeling Domain Relation Graph</u>



CMD Selection

- 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
    - First choose semantic domain for common ancestor domain *D*, then refine it in *C.*
  - Abstraction level – decided by primitives *P*
    - Explore different abstraction level by choosing different primitives.
    - Carried out when select *C* as child domain of *D.*
    - Utilize ancestor-child relation to explore candidate child domains formally.

Trade-off: complexity and size of mapping space

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Covering Problem Formulation

- 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_{ij}
  - Quantities (power, area, bandwidth…): Q_{ijk}^l
  - Costs (special quantities): C_{ijk}^l
- Constraints:
  - Decision constraints: $\sum_{j \in S_i} d_{ij} = 1 \quad \forall i, \ 1 \le i \le n$
    - Each function primitive instance needs to be <u>covered</u> by one and only one architecture primitive instance.
  - Quantity constraints: $H_t^l(d_{ij}, Q_{ijk}^l) \le QC_t^l$
    - Constraints from architecture platform or design constraints, such as power constraints, bandwidth constraints, etc.
- Objective function:
  - Cost function: $G_l(d_{ij}, C_{ijk}^l)$

Solve Covering Problem

General purpose solvers

- MILP: CPLEX, MOSEK, GLPK, …
- GP: GGPLAB, YALMIP, …

Domain-specific Algorithms

Covering Problem

$$\sum_{j \in S_i} d_{ij} = 1$$

$$H_t^l(d_{ij}, Q_{ijk}^l) \le QC_t^l$$

$$G_l(d_{ij}, C_{ijk}^l)$$

Other design concerns

Scheduling
Buffer sizing
Comm. bandwidth
……

Customizable Branch-based framework

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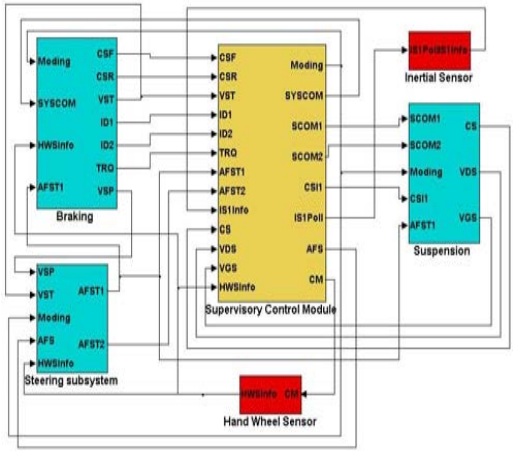
Automotive Stability Control

Find common language between functionality and architecture by choosing semantic domain Q in CMD $C_Q(P)$.

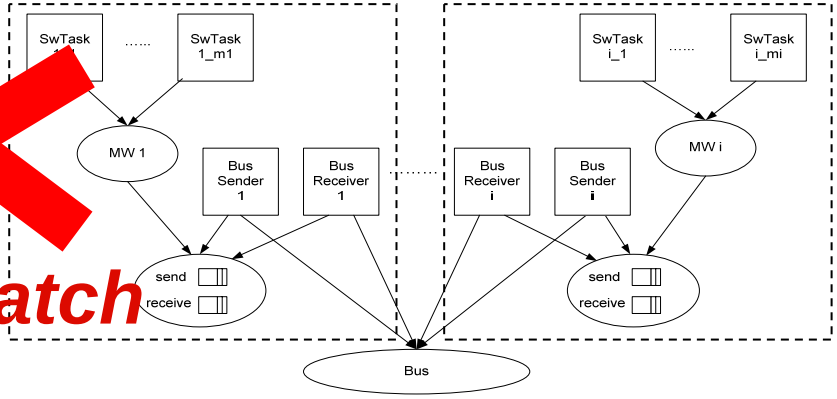
Functionality

- synchronous Simulink model
- no message loss or duplication



Architecture

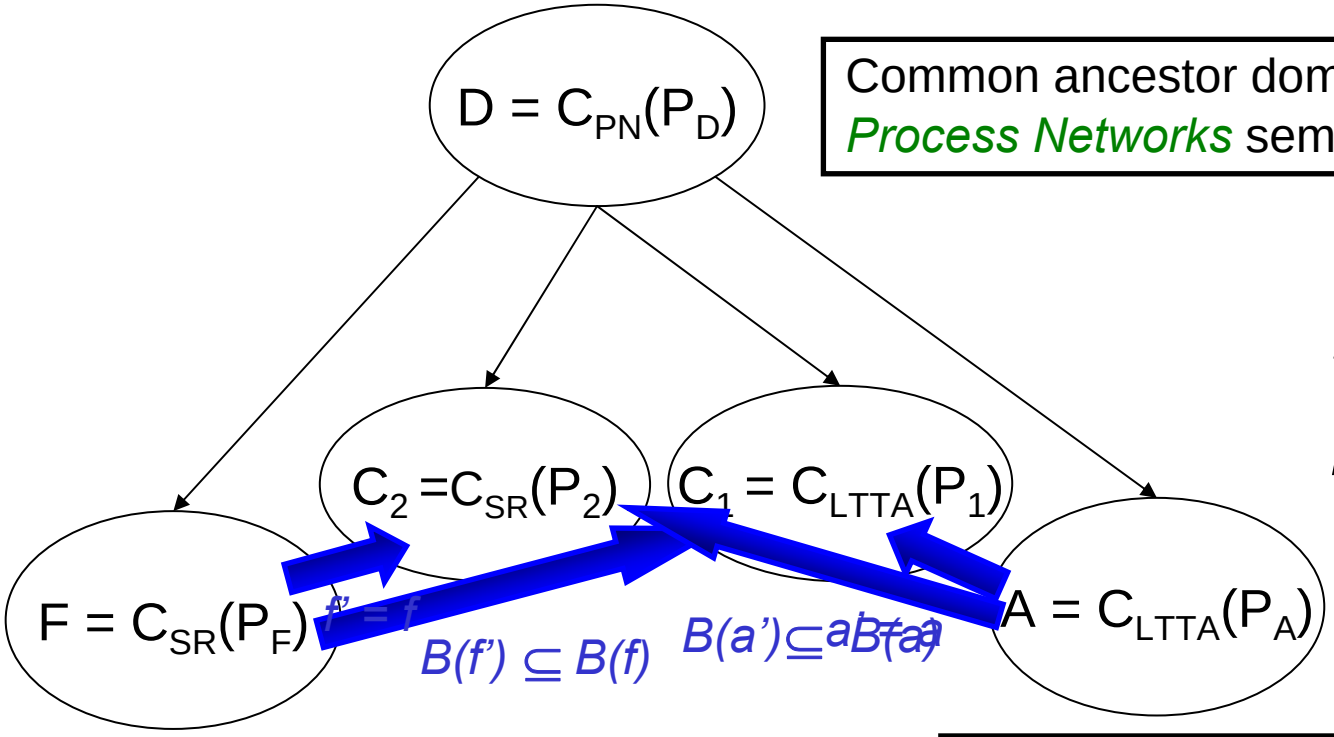
- clock drift between distributed ECUs, asynchronous comm.
- data loss and duplication



mismatch

CMD Selection (Stage 1)

- Find CMD from modeling domain relation graph



Common ancestor domain:
Process Networks semantics

$P_1 = P_{F'} \cup P_A$

$P_2 = P_F \cup P_{A'}$

Original Function modeling domain:
Synchronous/Reactive semantics

Original Architecture modeling domain:
Semantics of *LTTA*
(loosely time-triggered architecture)

[1] H. Zeng, A. Davare, A. L. Sangiovanni-Vincentelli, et. al, "Design Space Exploration of Automotive Platforms in Metropolis," SAE 2006

Transformation of architecture model

- CMD uses synchronous/reactive semantics
  - Function model does not need to be changed
  - Architecture primitives P_A should be transformed to $P_{A'}$ in CMD to support synchronous/reactive semantics
    - Protocol to avoid data loss [1]
      - Constraints on process periods
      - Requires clock drift to be within a certain range
    - Clock synchronization to restrict the clock drift [2]
    - Alternating bit to avoid data duplication
    - $B(a') \subseteq B(a)$, but correct behaviors can be assured when function model *f'* is mapped to architecture model *a'*

[1] A. Benveniste, P. Caspi, P. Le Guernic, H. Marchand, J.P. Talpin and Stavros Tripakis, “A Protocol for Loosely Time-Triggered Architectures”, EMSOFT '02

[2] M. Gergeleit and H. Streich, “Implementing a Distributed High-Resolution Real-Time Clock using the CAN-Bus”, 1st International CAN-Conference

Automatic Synthesis (Stage 2&3)

- Covering problem
  - Function primitives instance f_i : tasks and messages
  - Architecture primitives instance a_j : ECUs and buses
  - Quantity constraints : maximum workload on ECU
  - Objective function: minimize inter-ECU communication and balance computation load across ECUs
  - Utilize the Scotch [1] package
    - Function model graph and architecture graph
    - Partition-based algorithm solves the covering problem
- Further synthesis
  - Task priorities – based on pre-assigned message priorities
  - Task periods
    - Adjusted to satisfy end-to-end latency requirements
    - Task periods need to satisfy the protocol to ensure the correctness of semantics

[1] Scotch, http://www.labri.fr/perso/pelegrin/scotch

Experimental Results

- 14 tasks, 48 messages
- 6 ECUs, 1 bus
- Automatic synthesized design vs. 6 manual designs
- Simulated in Metropolis framework

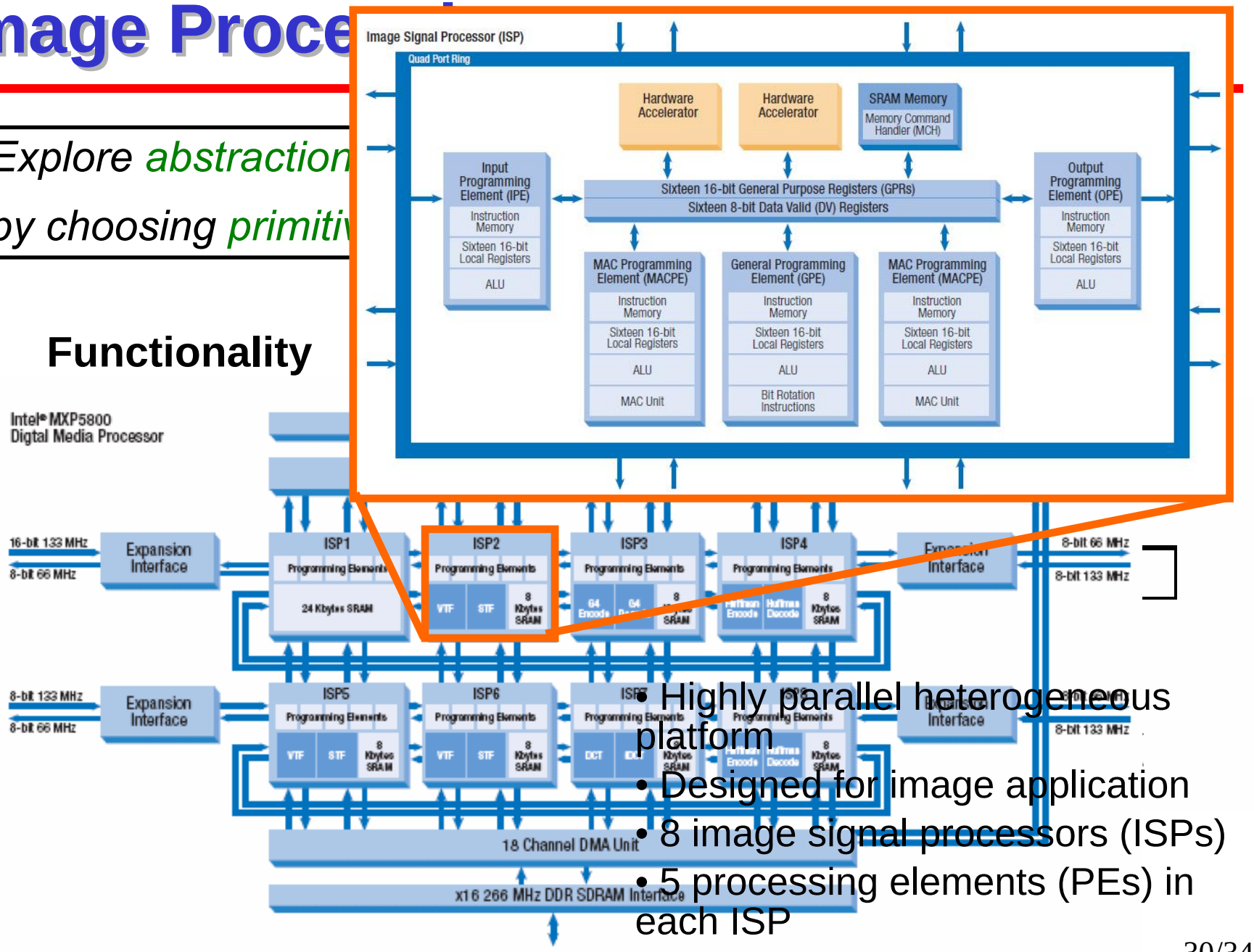
Design	Total delay (ms)	Bus utilization	Max ECU utilization
Manual 1	787.10	57%	60%
Manual 2	761.84	50%	72%
Automatic	559.51	34%	48%

Image Proce

Explore abstraction

by choosing primiti

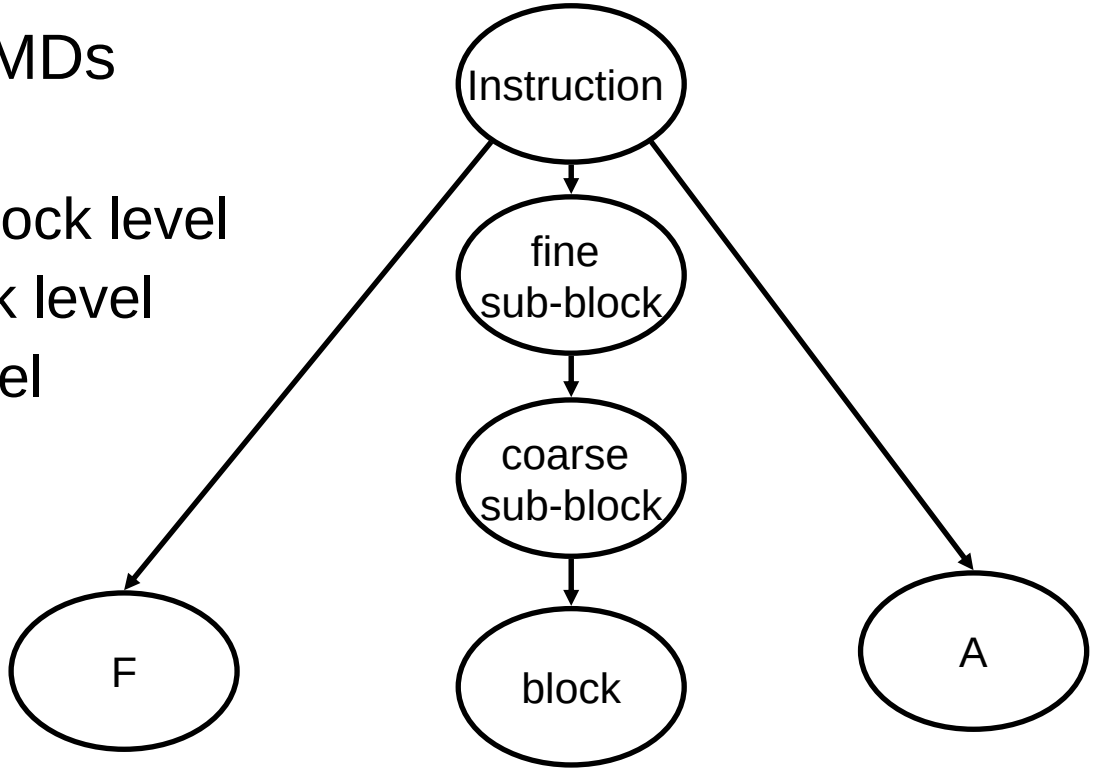
Functionality



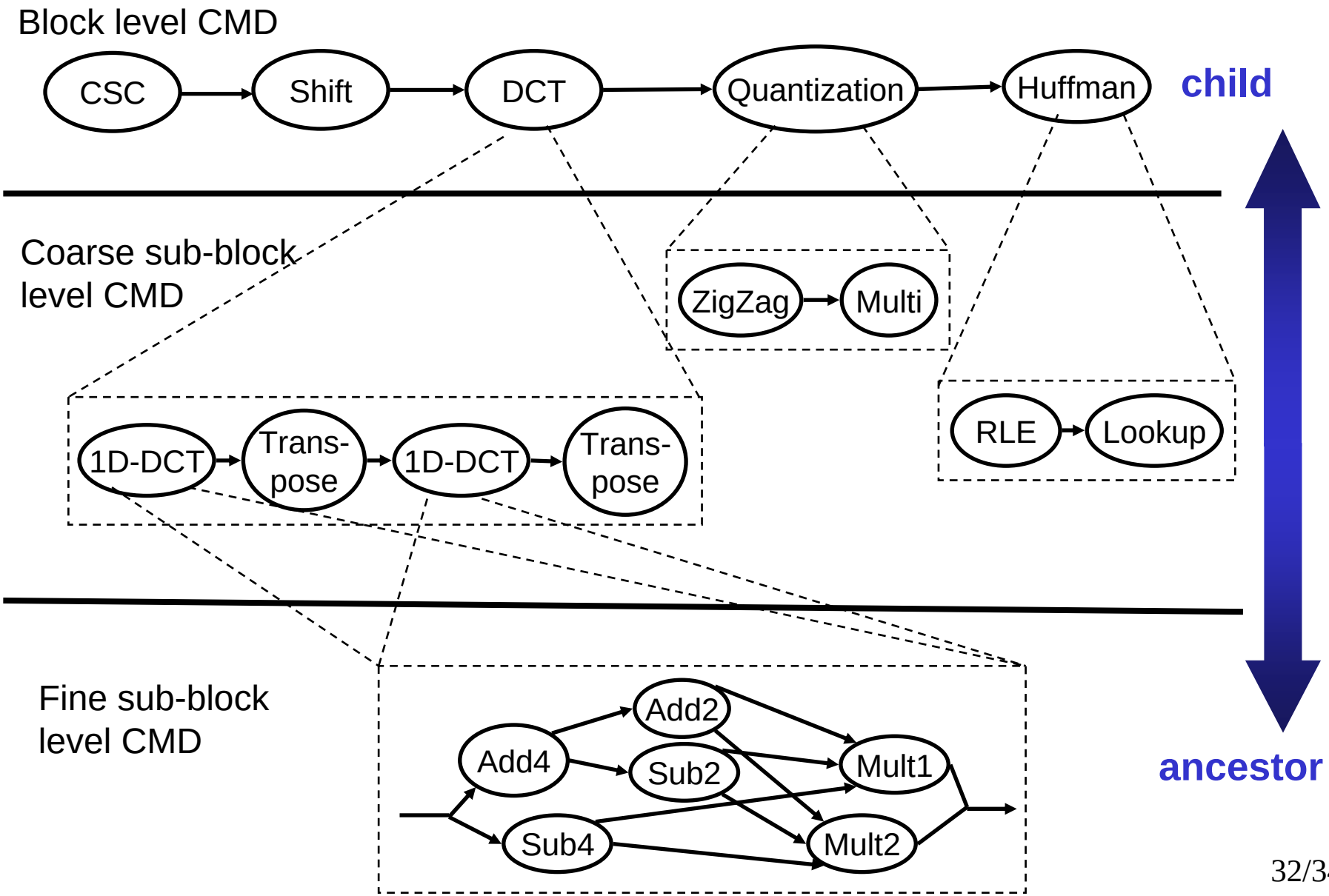
- Highly parallel heterogeneous platform
- Designed for image application
- 8 image signal processors (ISPs)
- 5 processing elements (PEs) in each ISP

CMD Selection (Stage 1)

- Dataflow semantics
- Choose proper abstraction level (granularity)
  - Too coarse – inefficient usage of highly parallel platform
  - Too fine – scheduling difficulties and model complexity
- Explored four CMDs
  - Block level
  - Coarse sub-block level
  - Fine sub-block level
  - Instruction level



Function Model at Different CMDs



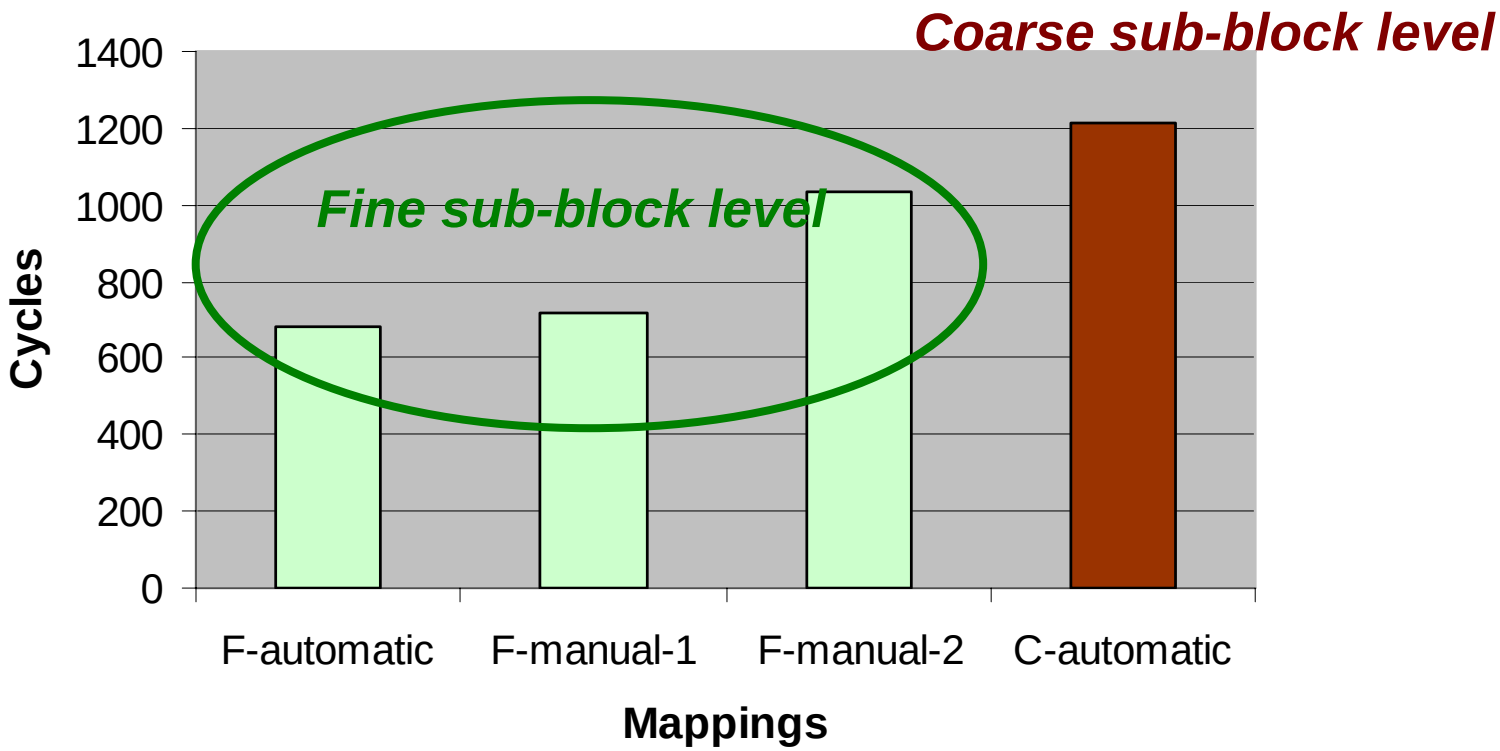
Architecture Model

- Architecture model has the same abstraction level in all CMDs for this case study.
  - PEs, global registers, memories are architecture primitives in all CMDs.
  - Abstraction levels of mapped designs in this case study are dictated by the functional abstraction levels.
- No single PE can support DCT block so block level CMD is not suitable.
- Complexity is too high so instruction level CMD is not suitable.

Important to find a CMD at proper abstraction level

Automatic Synthesis (Stage 2&3)

- Mapping at coarse and fine sub-block level CMDs.



Choosing a CMD at proper abstraction level can greatly affect the performance of the mapping.

[1] A. Davare, Q. Zhu, J. Moondanos and A. L. Sangiovanni-Vincentelli, "JPEG Encoding on the MXP5800: A Platform-based Design Case Study," EstiMedia 2005.

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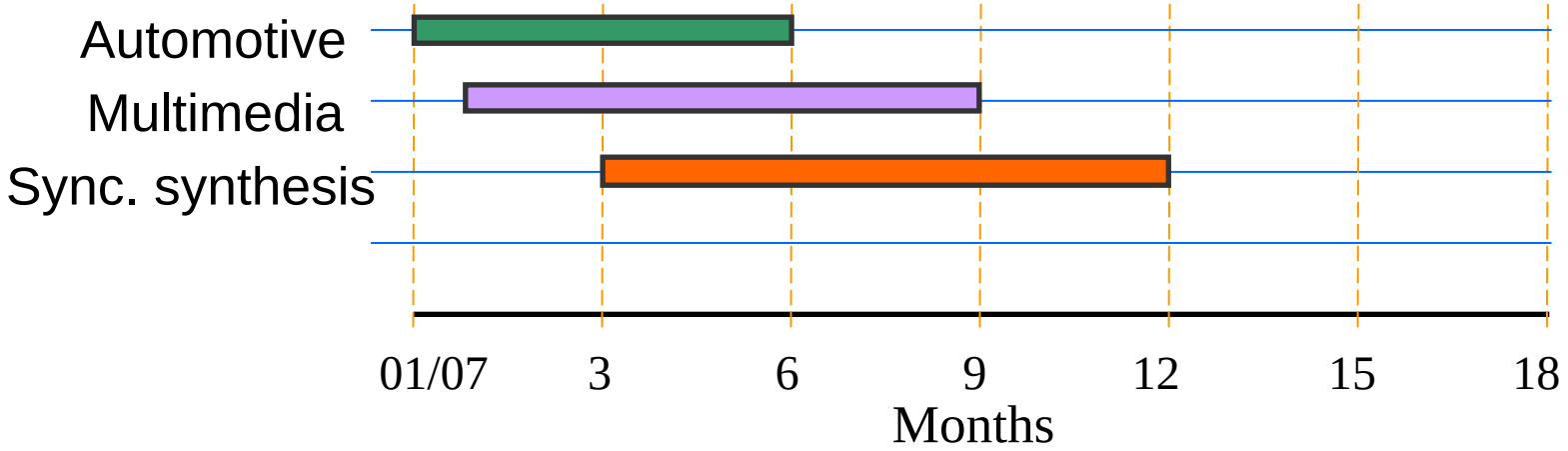
Future Work

- Ongoing projects:
  - Task allocation and priority assignment for automotive systems – stage 2
  - Period synthesis for automotive systems – stage 3
- Future work:
  - Complete synthesis flow for automotive domain
  - Multimedia domain case study – H.264
  - Synthesis from synchronous models to general multi-processor platform



Contributions

- A synthesis flow in which semantics and abstraction level are formally determined, and automatic algorithms can be applied.

- The method was validated by industrial case studies with different focus.
  - Automotive stability control: choose semantics
  - Image processing: explore abstraction level
  - Regardless of the focus, applications from different domains can be solved in the same way by our flow.