Technische Universiteit Eindhoven University of Technology

Forum on specification & Design Languages
FDL 2013

Making Data Flow, Dynamically

Twan Basten

Eindhoven University of Technology & TNO Embedded Systems Innovation

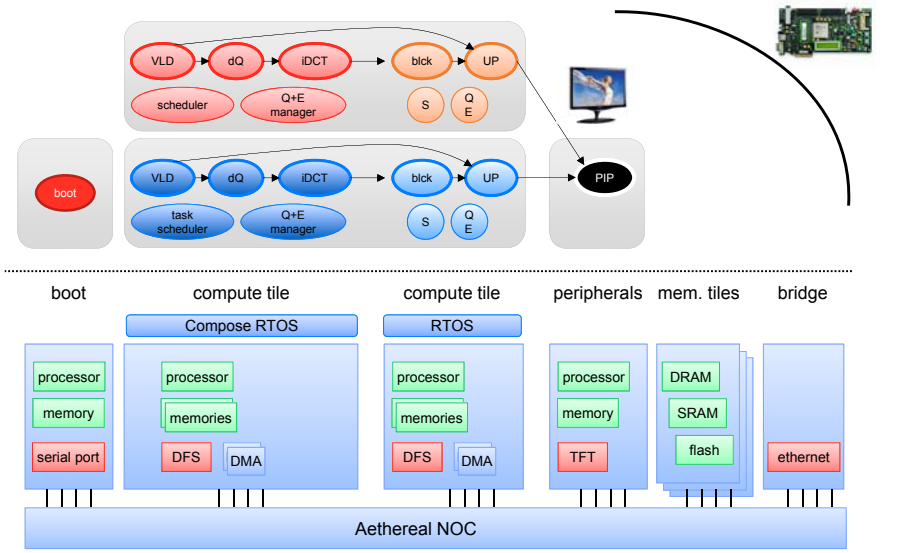
Joint work with
Marc Geilen, Sander Stuijk, Bart Theelen
and many others

'Knowing is not understanding.'
Charles Kettering

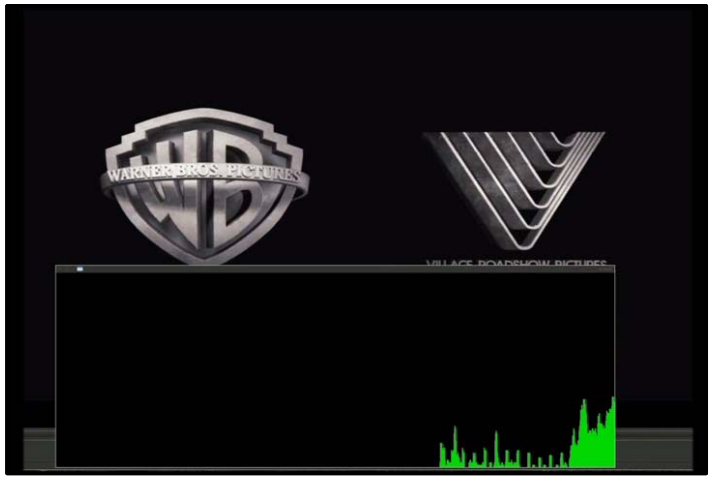
Predictable computing !?

3 CompSOC: a predictable MPSoC platform

4 CompSOC: a predictable MPSoC platform

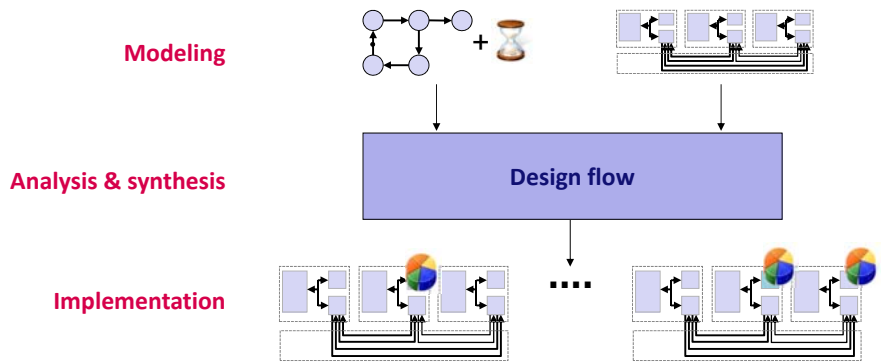


5 Challenge: Data-dependent data-processing workloads



6 Data-intensive systems are everywhere!

7 What we need: Model-driven design

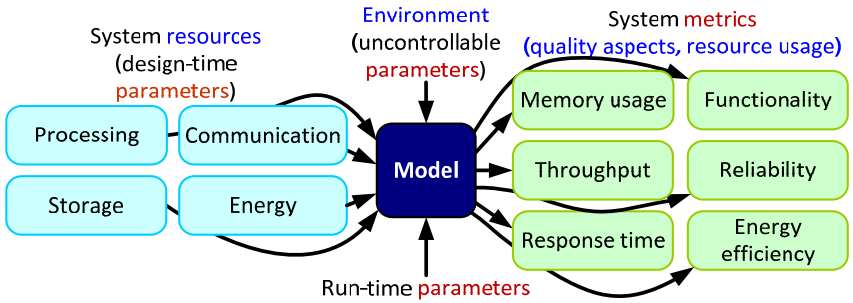


8 Outline

- Predictable computing !?
- Data flow models of computation
- SDF analysis and synthesis
- SADF analysis and synthesis
- Interaction
- Conclusions

Data flow models of computation

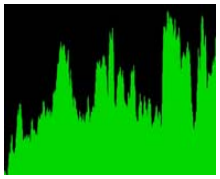
… predicts system metrics given parameter values

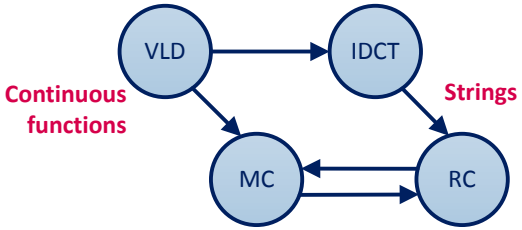


… should be targeted to the problem at hand

(KPN [Kahn 1974])

MPEG-4 SP:

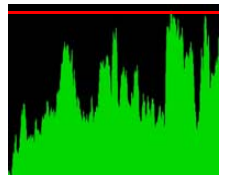


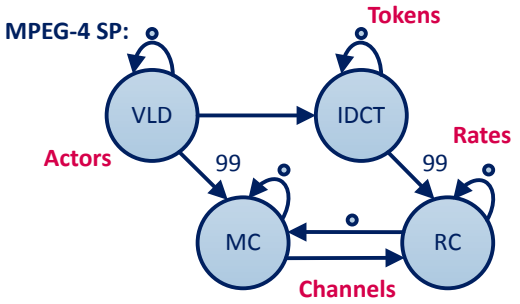


- Can express any continuous function on strings
- Captures "precisely" all streaming applications
- Doesn't capture interaction with the environment
- No analysis & synthesis (other than functionality)

(SDF [Lee 1986])

MPEG-4 SP:



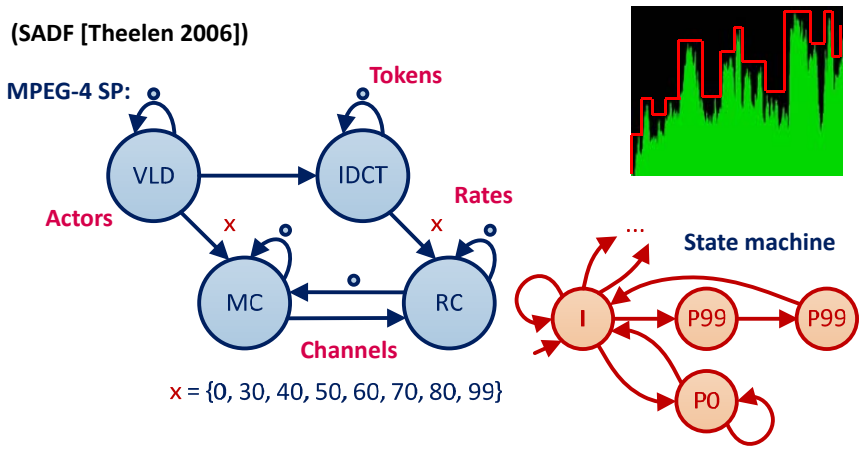


- Conservative, worst-case abstraction
- Strong analysis & synthesis support
- Low implementation overhead …
- … but may lead to over-allocation of resources

13 Scenario-Aware Data Flow

TU/e

(SADF [Theelen 2006])

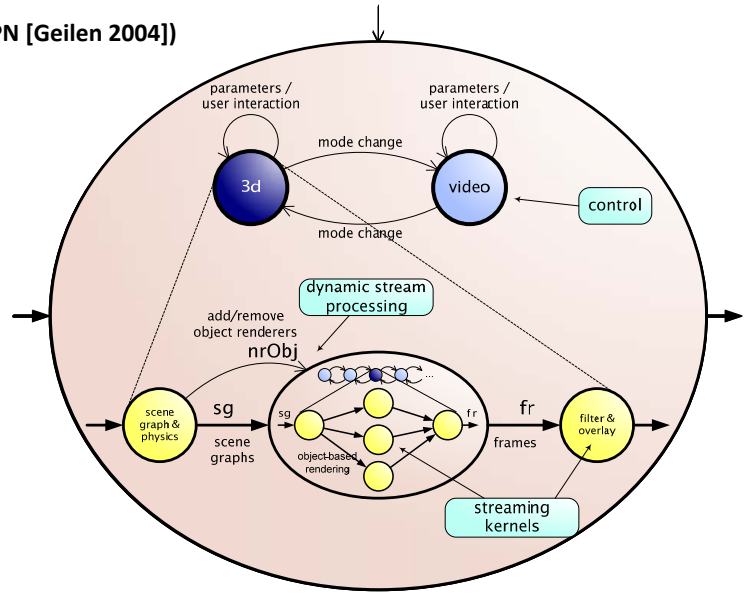


- Dynamics captured in scenarios
- Good compromise between expressivitiy, analysis & synthesis
- Efficient implementations

14 Reactive Process Networks: Adding interaction

TU/e

(RPN [Geilen 2004])

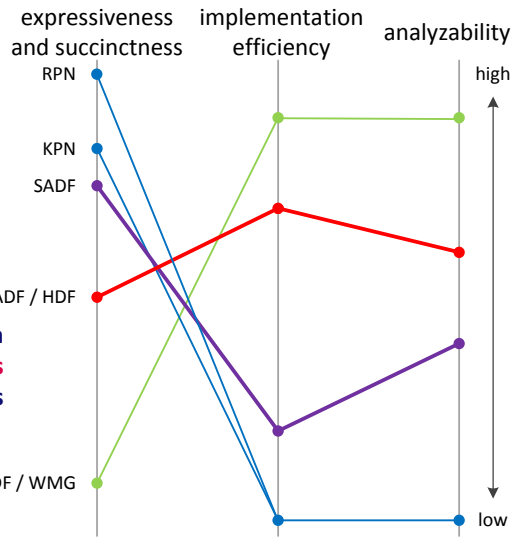


15 Comparison of data flow Models of Computation

TU/e

implementation efficiciency and analyzability vs. expressiveness are contradictory

but FSM-SADF provides a good compromise



SADF with Finite State Machines specifying scenario transitions

(SAMOS 2011)

16 Comparison of data flow Models of Computation

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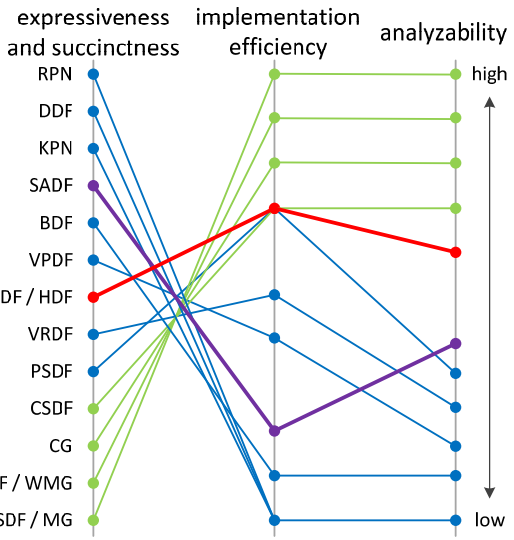
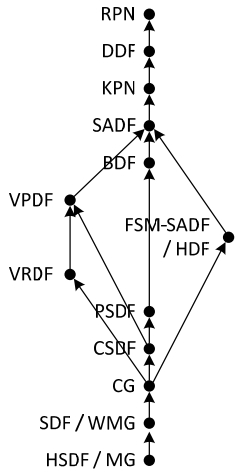


SADF with Finite State Machines specifying scenario transitions

(SAMOS 2011)

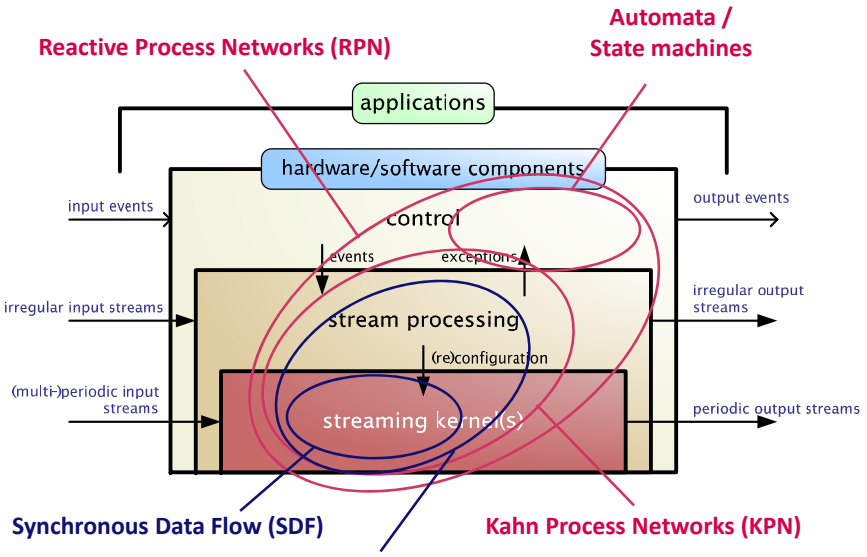
17 Data flow Models of Computation: Expressiveness hierarchy



- Known or straightforward inclusion relations
- BDF and above: Turing complete
- Better expressiveness notions needed
- Unification needed

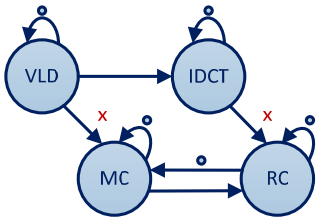
(SAMOS 2011)

18 Targeting models to the problem at hand

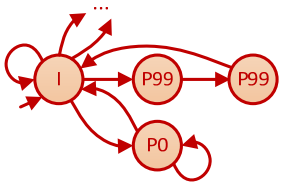


19 Targeting models to the problem at hand is important

2-processor implementation of MPEG4-SP



x = {0, 30, 40, 50, 60, 70, 80, 99}



SDF

Execution times	
VLD	33
IDCT	14
MC	325
RC	292

Data rate	
x	99

SADF

Execution times		
VLD	P0	0
	other	33
IDCT	P0	0
	other	14
MC	I,P0	0
	P30	75
	P40	121
	P50	158
	P60	196
	P70	221
	P80	258
	P99	325
RC	I	292
	P0	0
	P30,40,50	208
	P60	250
	P70,80,99	267

Actor worst-cases occur for different scenarios

20 Targeting models to the problem at hand is important

MPEG4-SP				MP3
metric	SDF	SADF	improvement	improvement
throughput	15 (frames/s)	15 (frames/s)	NA	NA
processor capacity	88 %	26 %	70 %	-
memory capacity	254 KB	254 KB	-	21 %
bandwidth	33 %	33 %	-	23 %

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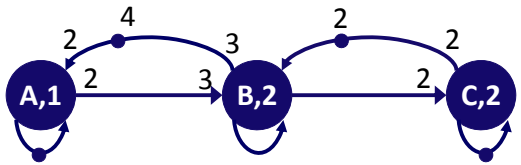
SDF
analysis and synthesis

SDF: Iterations



Iteration

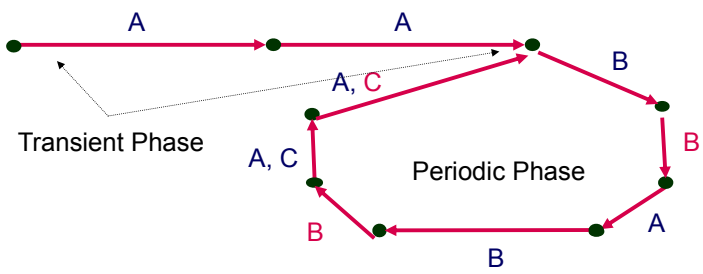
smallest non-empty set of actor firings
that does not change the token distribution

(example: A:3, B:2, C:1)

Crucial concept in data flow analysis

SDF throughput analysis

Self-timed execution:



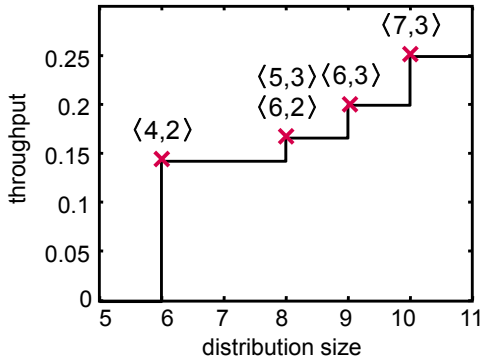
Throughput: average number of actor firings over time

Throughput can be calculated from the periodic phase

Efficient implementation
Consider one designated firing per iteration only to detect a recurrent state

(ACSD 2005)

25 Storage vs. throughput trade offs



- Separate buffer per channel
- Storage distribution, e.g., $\langle \alpha, \beta \rangle \rightarrow \langle 4,2 \rangle$

Find all minimal storage distributions for any possible throughput

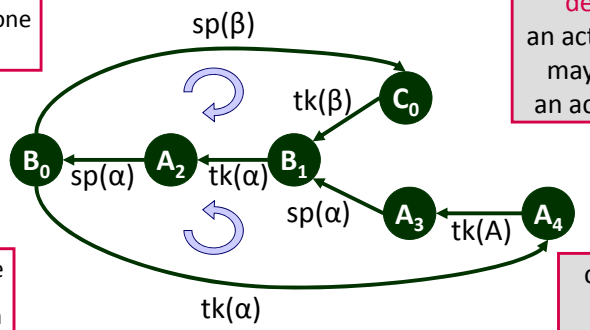
(DAC 2006, TC 2008)

26 Storage vs. throughput: Dependency graph

Storage distribution $\langle \alpha, \beta \rangle \rightarrow \langle 4,2 \rangle$

firings in one period

dependency: an actor firing start may depend on an actor firing end



sp - space

tk - token

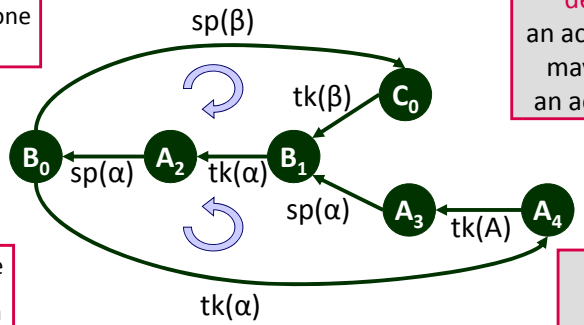
cycles denote storage dependencies

27 Storage vs. throughput: Dependency graph

resolving storage dependencies may increase throughput

firings in one period

dependency: an actor firing start may depend on an actor firing end



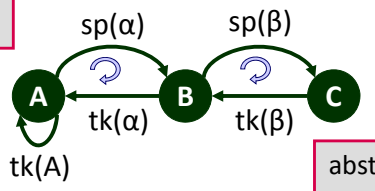
sp - space

tk - token

cycles denote storage dependencies

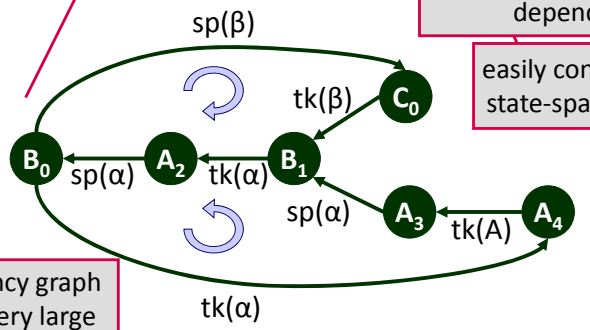
28 Storage vs. throughput: Abstract dependency graph

dependencies between actors



abstract dependency graph contains all storage dependencies

easily constructed from state-space exploration



dependency graph may be very large

(DAC 2006, TC 2008)

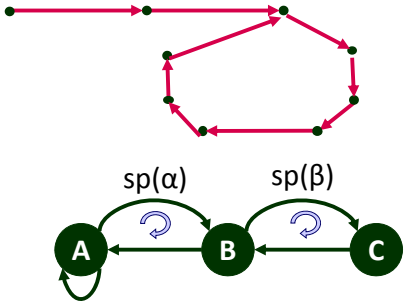
29 Storage vs. throughput trade offs

- Repeated throughput analysis
- Start small, recursively resolve bottlenecks
- Fast in general, approximation possible
- Generalizable to other resources, computational models

(DAC 2006, TC 2008)

30 Lessons learned: key concepts

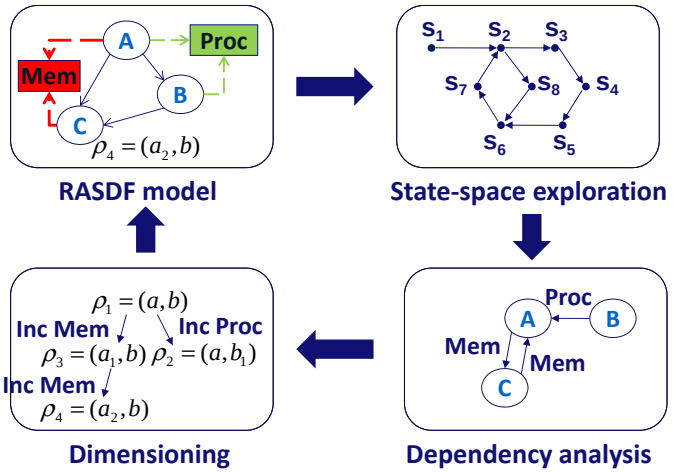
- Iterations
- State-space exploration
- Storage dependencies
- Abstract dependency graph



These concepts are re-usable !

31 Application: resource sharing

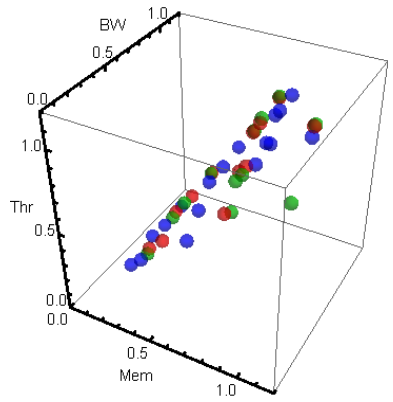
(Resource-Aware SDF, RASDF [Yang 2009])



(DATE 2010)

32 Application: resource sharing

(Resource-Aware SDF, RASDF [Yang 2009])

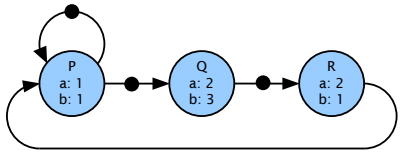


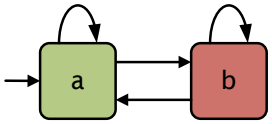
- Printer architecture exploration
- 3 architectures (colors)
- Throughput, memory, bandwidth trade offs

(DATE 2010)

- Predictable computing
- Data flow models of computation
- SDF analysis and synthesis
- SADF analysis and synthesis
- Interaction
- Conclusions

SADF analysis and synthesis

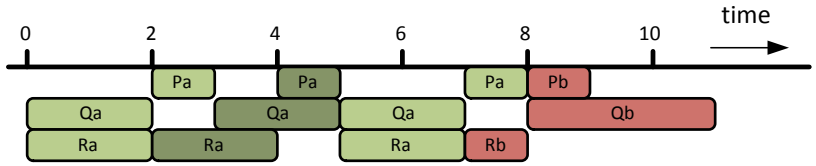


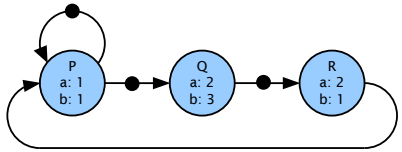


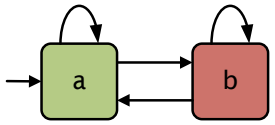
- SADF graph with two scenarios a and b
- Each iteration executes in one scenario
- Analysis based on (max, +)-algebra

(CODES+ISSS 2010)

- Gantt chart for the scenario sequence aaab





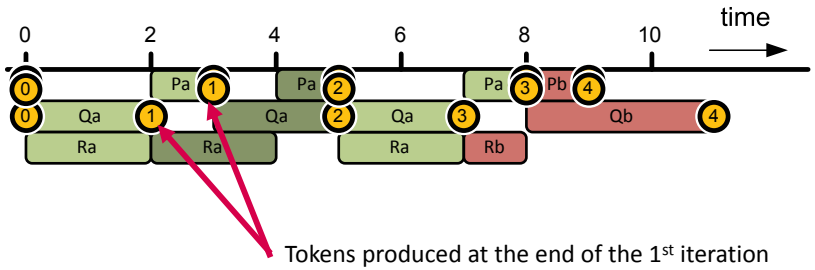


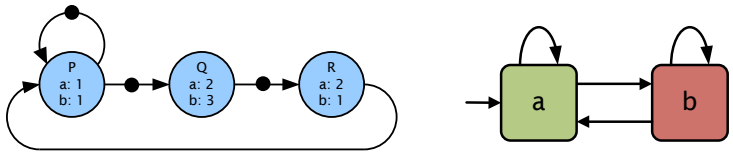
(CODES+ISSS 2010)

37 SADF throughput analysis

TU/e

- Gantt chart for the scenario sequence aaab



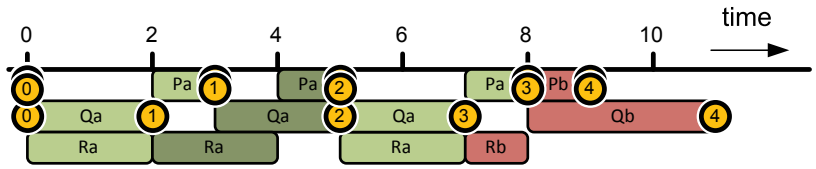


(CODES+ISSS 2010)

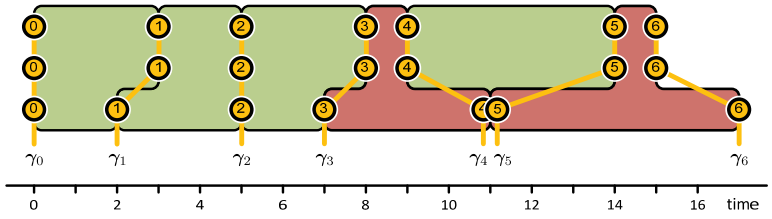
38 SADF throughput analysis: time-stamp vectors

TU/e

- Gantt chart for the scenario sequence aaab



- Execution is a sequence of vector shapes
- Is nicely captured by matrix multiplication in (max,+)-algebra

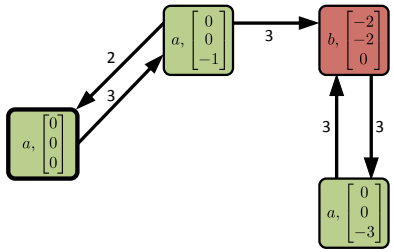


(CODES+ISSS 2010)

39 SADF throughput analysis: state-space analysis

TU/e

- State space of the SADF



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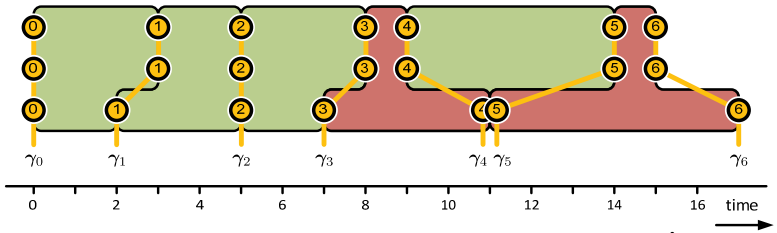
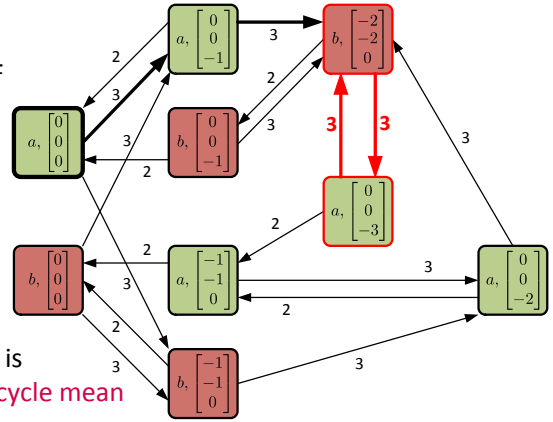


(CODES+ISSS 2010)

40 SADF throughput analysis: state-space analysis

TU/e

- State space of the SADF



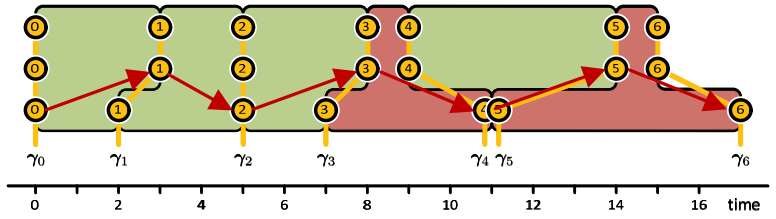
- Worst-case throughput is the inverse of the max cycle mean

(CODES+ISSS 2010)

41 SADF throughput analysis: (Max,+)-automata

TU/e

- Critical path is through token dependencies

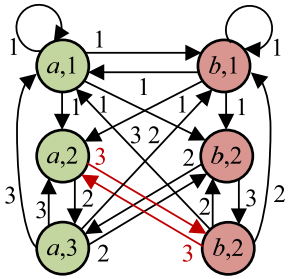


(CODES+ISSS 2010)

42 SADF throughput analysis: (Max,+)-automata

TU/e

- (Max,+)-automaton
- Worst-case throughput is again the inverse of the max cycle mean



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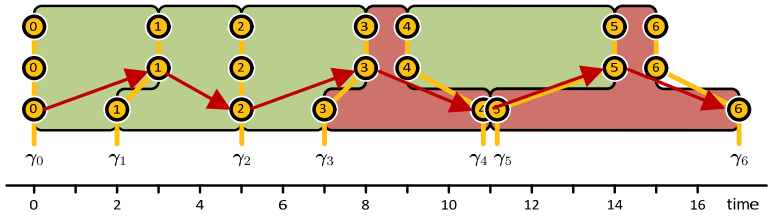


(CODES+ISSS 2010)

43 Model-driven SADF design flow: the SDF3 toolkit

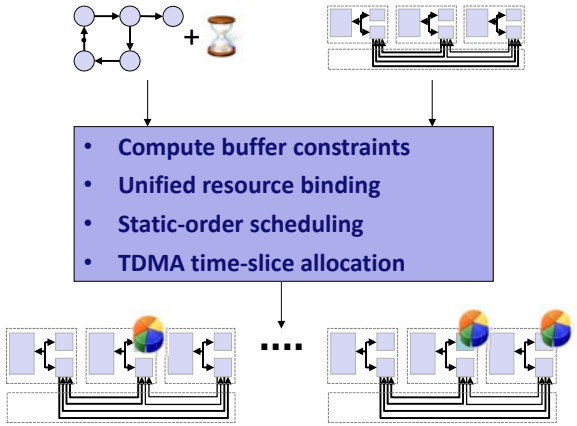
TU/e

Modeling

Analysis & synthesis

- Compute buffer constraints
- Unified resource binding
- Static-order scheduling
- TDMA time-slice allocation

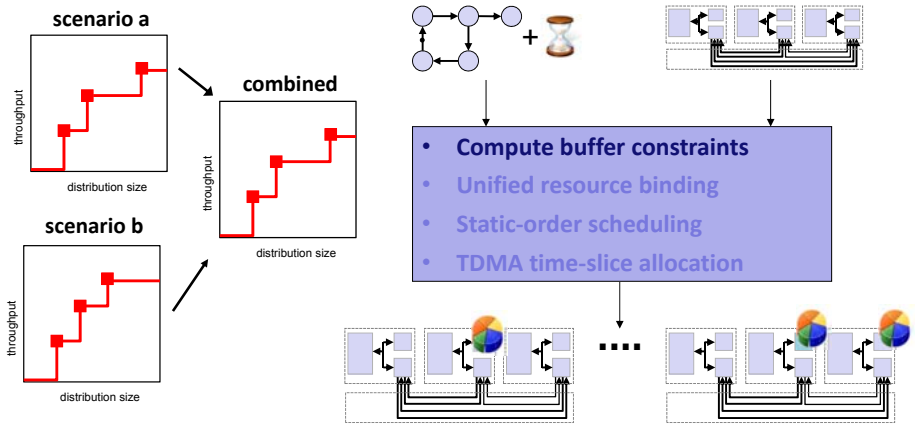
Implementation



(DSD 2010, www.es.ele.tue.nl/sdf3)

44 Model-driven SADF design flow: buffering

TU/e

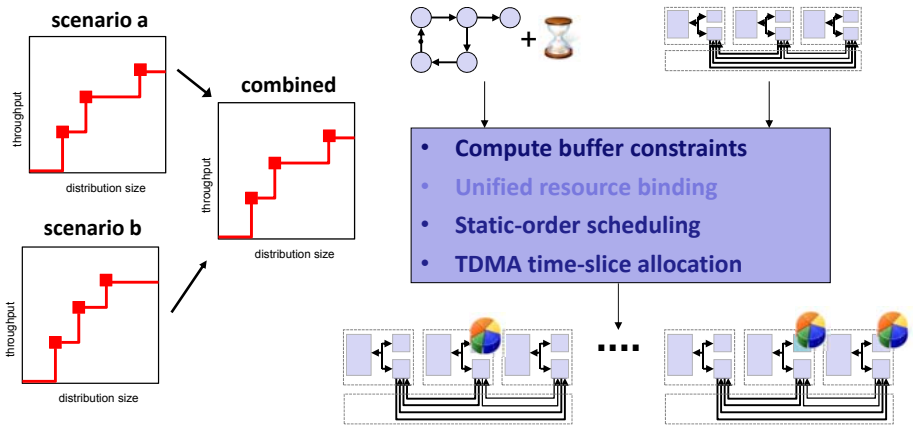


Open problem

Buffer analysis directly on SADF

(DSD 2010, www.es.ele.tue.nl/sdf3)

Model-driven SADF design flow: buffering



Open problem

Buffer analysis directly on SADF

Partly open problem

Modeling schedule(r)s

(DSD 2010, www.es.ele.tue.nl/sdf3)

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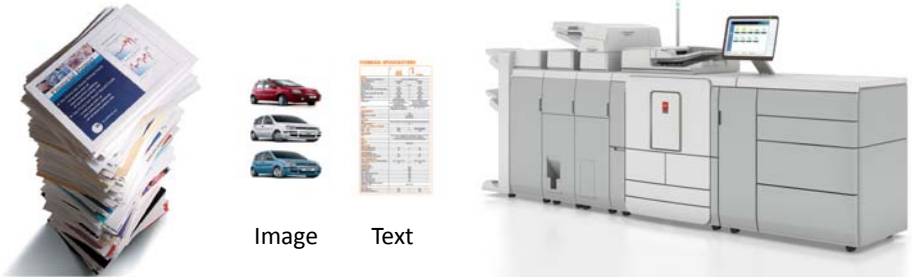
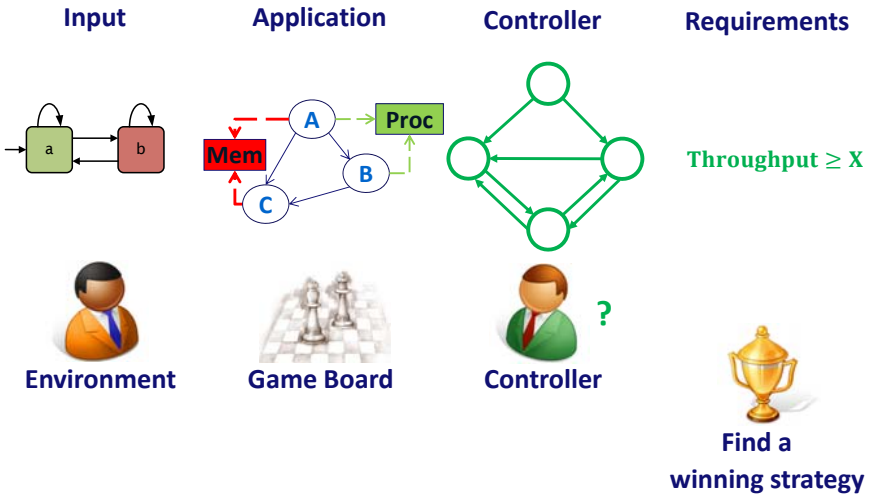
Interaction

Interaction between environment and data flow application



- Can throughput be guaranteed ?
- Can energy usage be optimized under a throughput constraint ?

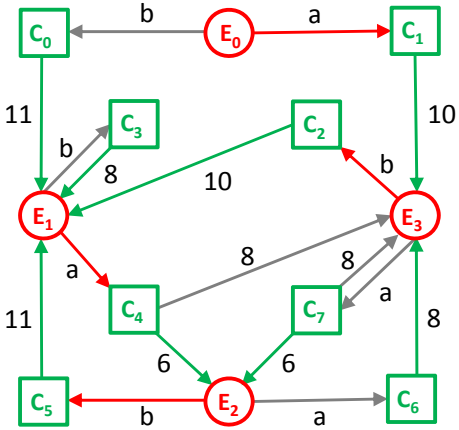
49 Realizing guaranteed throughput becomes a game



(DATE 2012)

50 Controller is constructed by solving a mean payoff game

- Game graph can be derived from SADF graph
- For every input scenario, controller executes a pre-defined schedule with the indicated latency
- Solved by policy iteration
  - Red encodes the worst-case input
  - Green encodes the optimal controller



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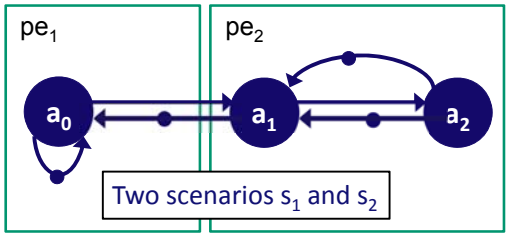
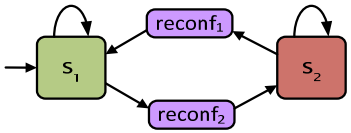
51 Dynamic Frequency and Voltage Scaling

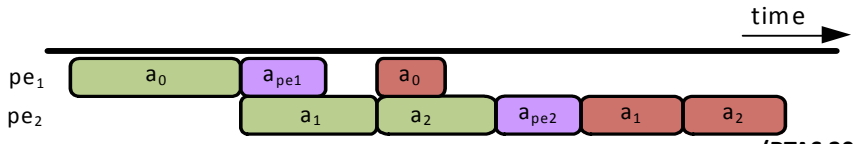
SADF model of mapped application, including reconfigurations





- Find frequency scale factor per processor per scenario
- within throughput constraint
- minimizing energy

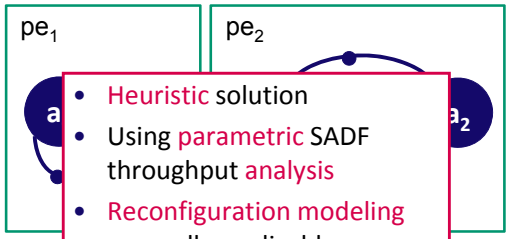
Reconfiguration SDF graphs



(RTAS 2013)

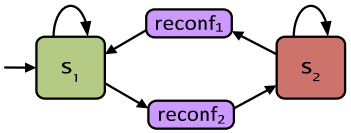
52 Dynamic Frequency and Voltage Scaling

SADF model of mapped application, including reconfigurations



- Heuristic solution
- Using parametric SADF throughput analysis
- Reconfiguration modeling generally applicable
- Game-theoretic solution ?

Reconfiguration SDF graphs



- Find frequency scale factor per processor per scenario
- within throughput constraint
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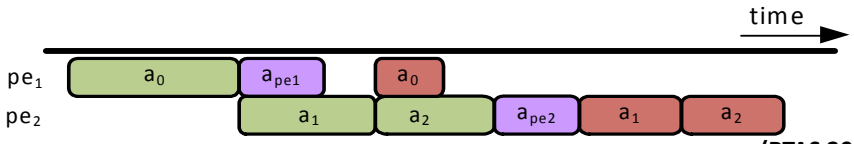


(RTAS 2013)

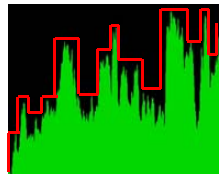
53 Outline

- Predictable computing
- Dataflow models of computation
- SDF analysis and synthesis
- SADF analysis and synthesis
- Interaction
- Conclusions

54 Conclusions

- Data flow MoCs:
  - Increasingly important
  - Good compromise between expressivity and analyzability
  - Synthesis feasible, leading to efficient implementations
- SDF3: Fully operational flow from SDF to CompSOC-FPGA platform
- Challenges: Coping with dynamics
  - Expressivity, unification of MoCs
  - Modeling mapping decisions
  - Predictable reconfiguration
  - Buffer analysis
  - Resource sharing
  - Controller synthesis
  - …

It's an exciting field !



55 Thank you !

Questions ?

More info: **www.es.ele.tue.nl/~tbasten/**

SDF3 toolkit: **www.es.ele.tue.nl/sdf3/**
CompSOC: **www.compsoc.eu**

Twan Basten