Verification of Real-Time Systems

Predictability and Predictable Microarchitectures

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Advanced Lecture, Summer 2015

Notion of Predictability

Oxford Dictionary:

- predictable = adjective, able to be predicted
- to predict = verb, state that a specified event will happen in the future

Fuzzy term in the WCET community.

May refer to the ability to predict:

- the WCET precisely,
- the execution time precisely,
- the WCET efficiently.

How are these related?

Ability to predict the WCET precisely

In theory we can precisely “predict” (rather: determine) the WCET of most systems:

- enumerate all inputs
- enumerate all initial states of microarchitecture
- enumerate all possible environments

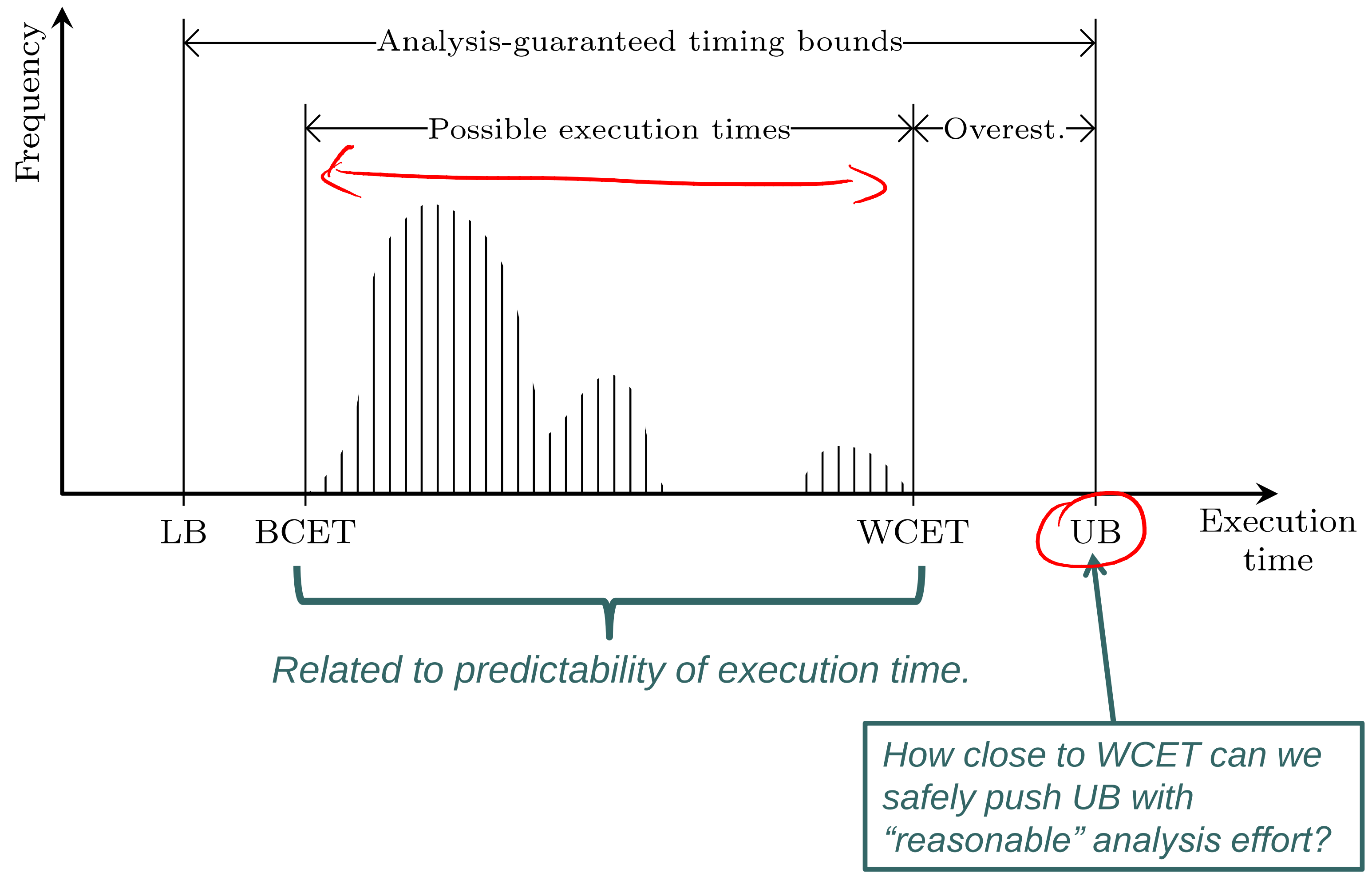
However, this is of course not feasible in practice.

→ Predictability of WCET is not the “right goal”

Contrast with ability to predict execution time:

→ Related to variability in execution times

Variability of Execution Times



Notion of Predictability

Fuzzy term in the WCET community.

May refer to the ability to predict:

- ~~the WCET precisely~~,
- the execution time precisely
  → execution-time predictability
- the WCET efficiently
  → analyzability

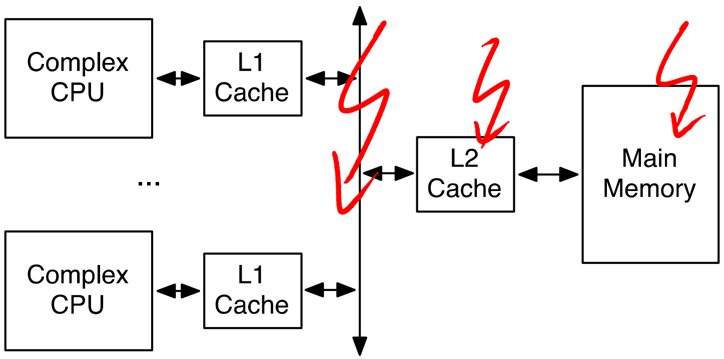
Challenges to Timing Predictability

Uncertainty about

- program inputs,
- initial state of microarchitecture, and
- activity in environment (e.g. other cores in multi-core), resulting in interference

→ introduces variability in execution times,
 thus decreases execution-time predictability.

→ introduces non-determinism in analysis,
 thus decreases analyzability.



Two Ways to Increase Predictability

1. Reduce uncertainty.
2. Reduce influence of uncertainty on
   a. Variability of execution times, and/or
   b. Analysis efficiency.

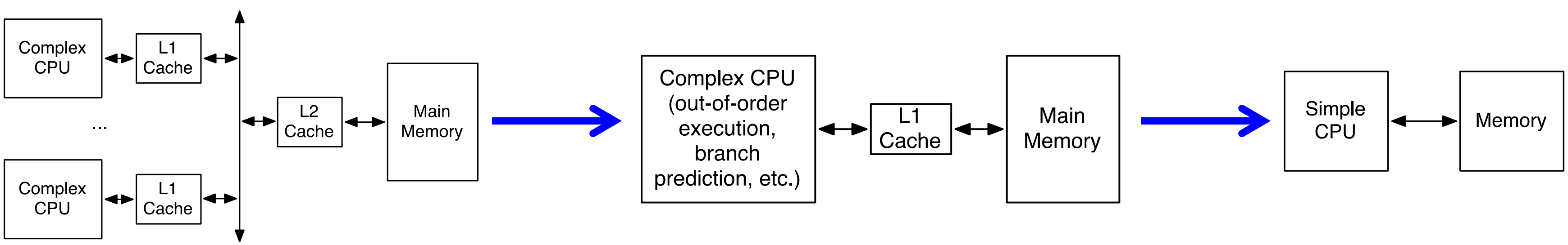
1. Reduce Uncertainty

- Reduce number of program inputs?

  Difficult…

- Reduce number of micro-architectural states:

  E.g. eliminate branch predictor, cache, out-of-order execution…



If done naively: Reverses many micro-architectural developments…
→ Decreases performance…
Key question: How to reduce uncertainty without sacrificing performance?

2.a) Reducing Influence of Uncertainty on Variability of Execution Times

If a source of uncertainty has no influence on execution times, it is irrelevant for timing analysis.

Example: Temporal Isolation

Temporal Isolation

- Temporal isolation between cores =

timing of program on one core is independent of activity on other cores

- Formally:

$$T(P_1, \langle p_1, c_1, p_2, c_2 \rangle) = T_{isolated}(P_1, \langle p_1, c_2 \rangle)$$

- Can be exploited in WCET analysis:

$$WCET(P_1) = \max_{p_1, c_1, p_2, c_2} T(P_1, \langle p_1, c_1, p_2, c_2 \rangle)$$
$$= \max_{p_1, c_1} T_{isolated}(P_1, \langle p_1, c_1 \rangle)$$

Temporal Isolation
How to achieve it?

- Partition resources in space and/or time
  - Resource appears like a slower and/or smaller private resource to each client
- Examples:
  - Time-division multiple access (TDMA) arbitration in shared busses
  - Partitioned shared caches

- Why not simply provide private resources then?

2.b) Reducing Influence of Uncertainty on Analysis Efficiency

Does non-determinism have to be a problem for analyzability?

- → Timing Anomalies
- → Domino Effects
- → Lack of Timing Compositionality

- Eliminate Timing Anomalies,

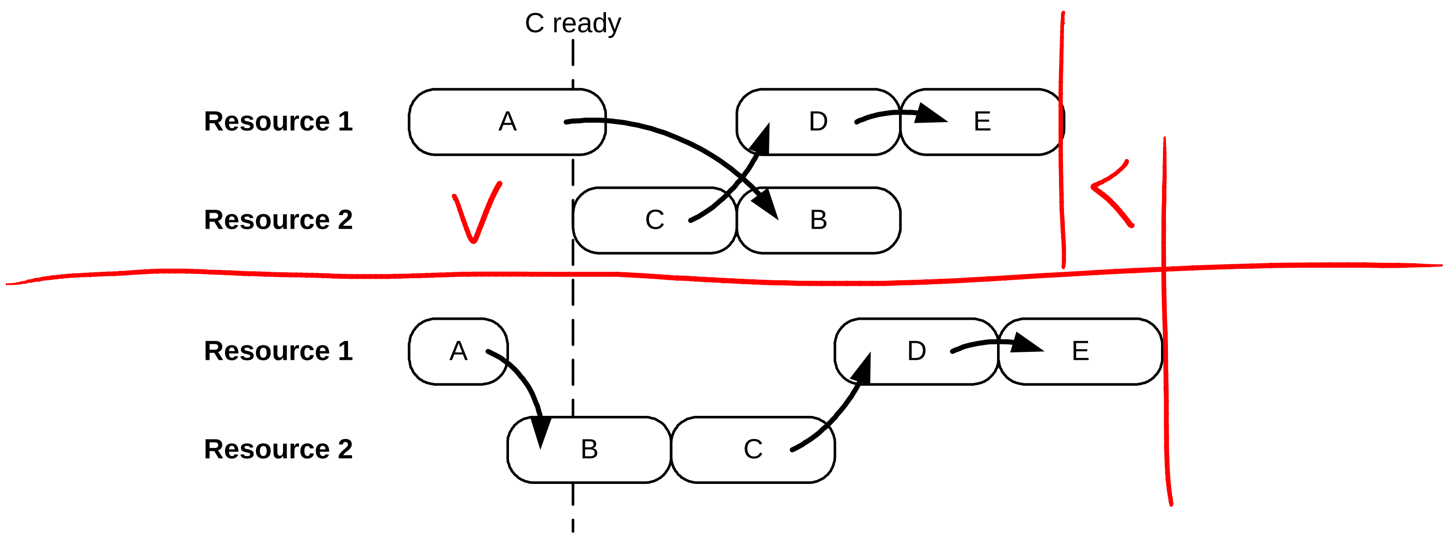
  e.g. stall pipeline on cache miss and use LRU.
- Eliminate Domino Effects

  e.g. use LRU rather than FIFO.

Timing Anomalies

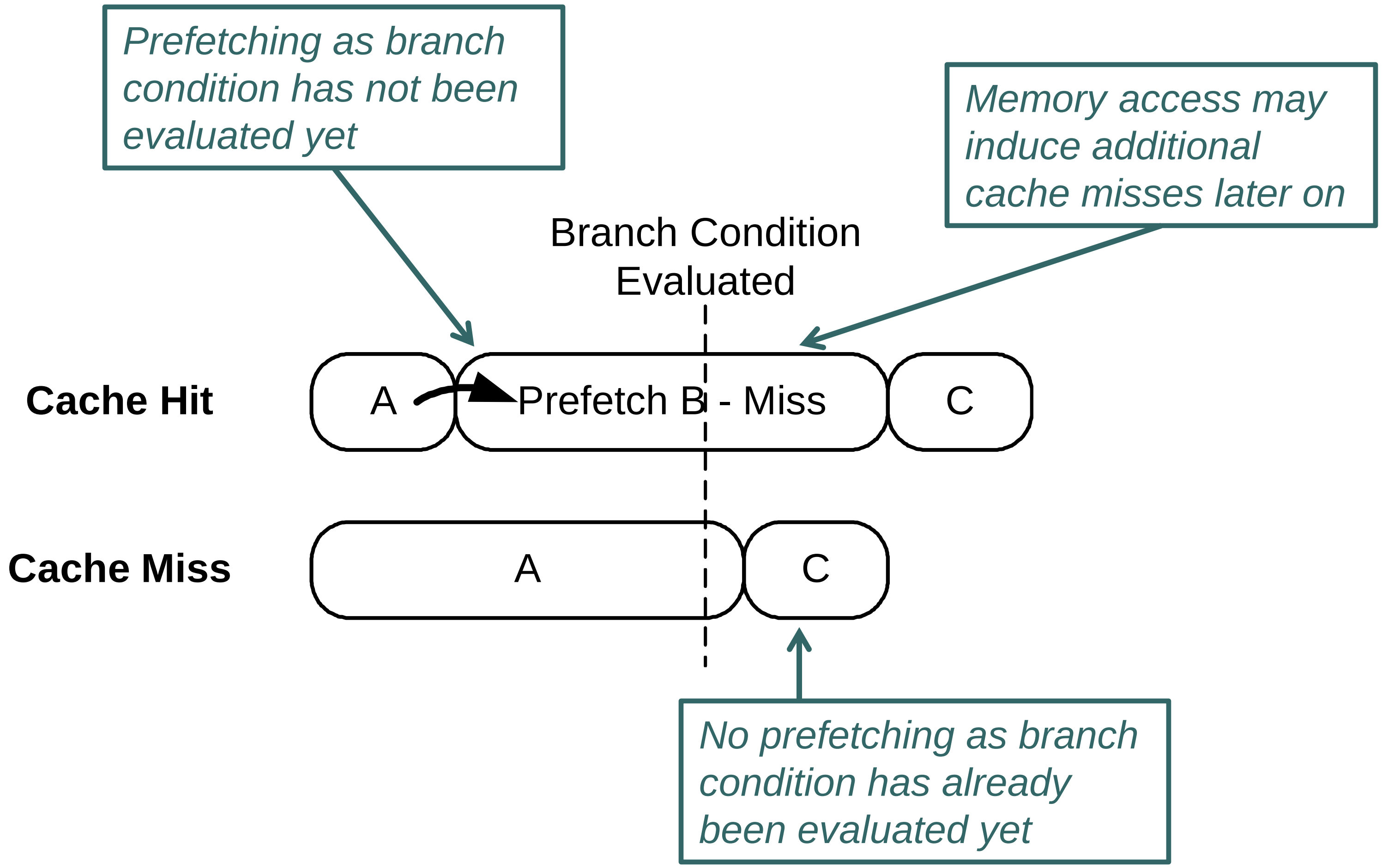
Timing Anomaly = Counterintuitive scenario in which the "local worst case" does not imply the "global worst case".

Example: Scheduling Anomaly

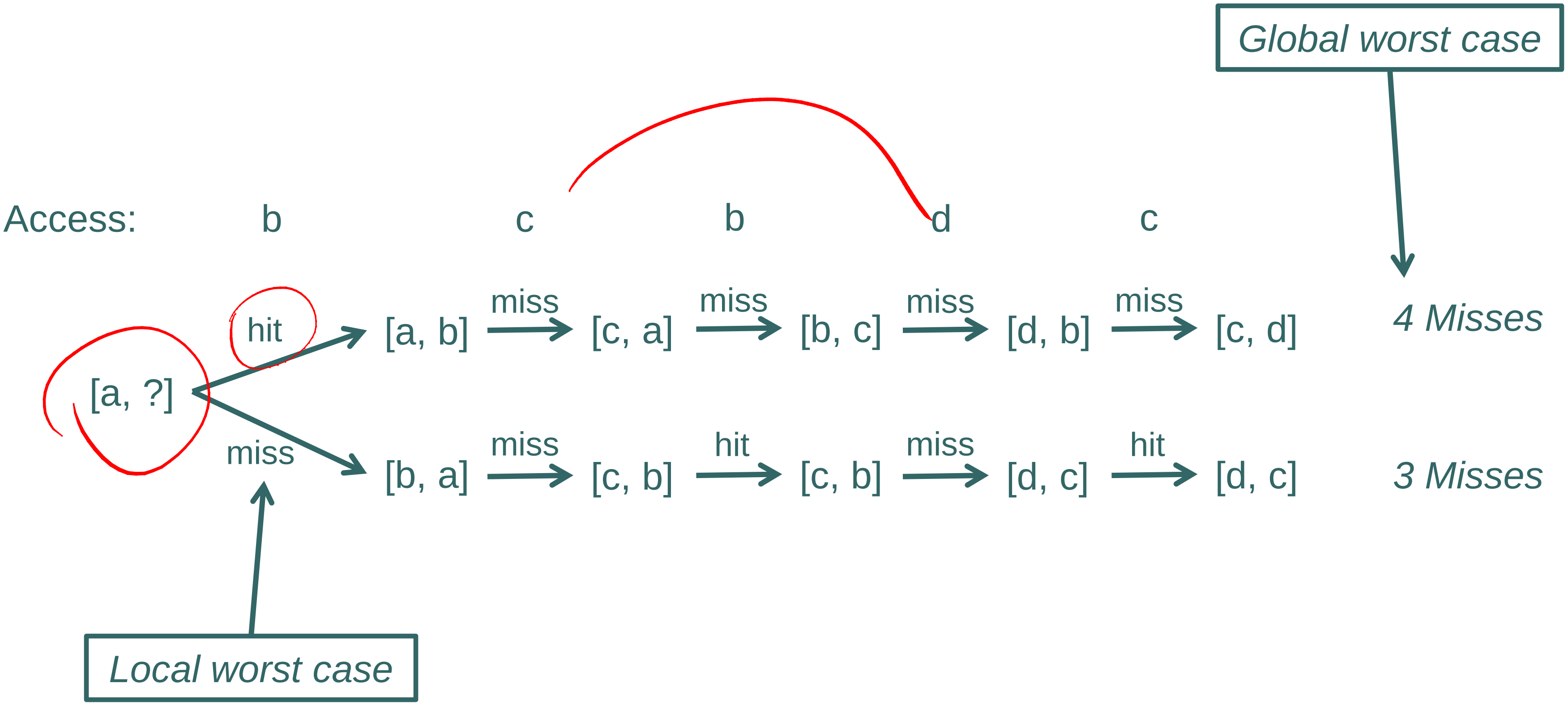


Recommended literature: *Bounds on multiprocessing timing anomalies*
RL Graham - SIAM Journal on Applied Mathematics, 1969 – SIAM
(http://epubs.siam.org/doi/abs/10.1137/0117039)

Timing Anomalies
Example: Speculation Anomaly



Timing Anomalies
Example: Cache Timing Anomaly of FIFO

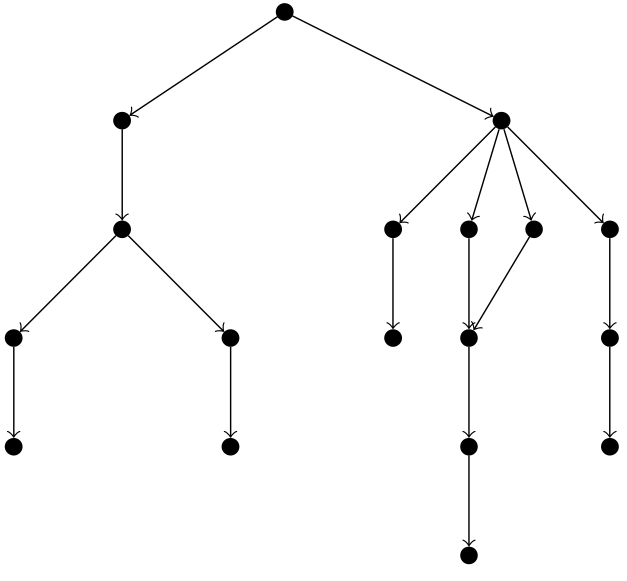


Similar examples exist for PLRU and MRU.
Impossible for LRU.

Timing Anomalies
Consequences for Timing Analysis

In the presence of timing anomalies, a timing analysis cannot make decisions “locally”: it needs to consider all cases.

→ May yield “State explosion problem”



Timing Anomalies
Open Analysis and Design Challenges

- How to determine whether a given timing model exhibits timing anomalies?
- How to construct processors without timing anomalies?
  - Caches: LRU replacement
  - No speculation
  - Other aspects: "halt" everything upon every "timing accident" → possibly very inefficient
- How to construct conservative timing model without timing anomalies?
  - Can we e.g. add a "safety margin" to the local worst case?

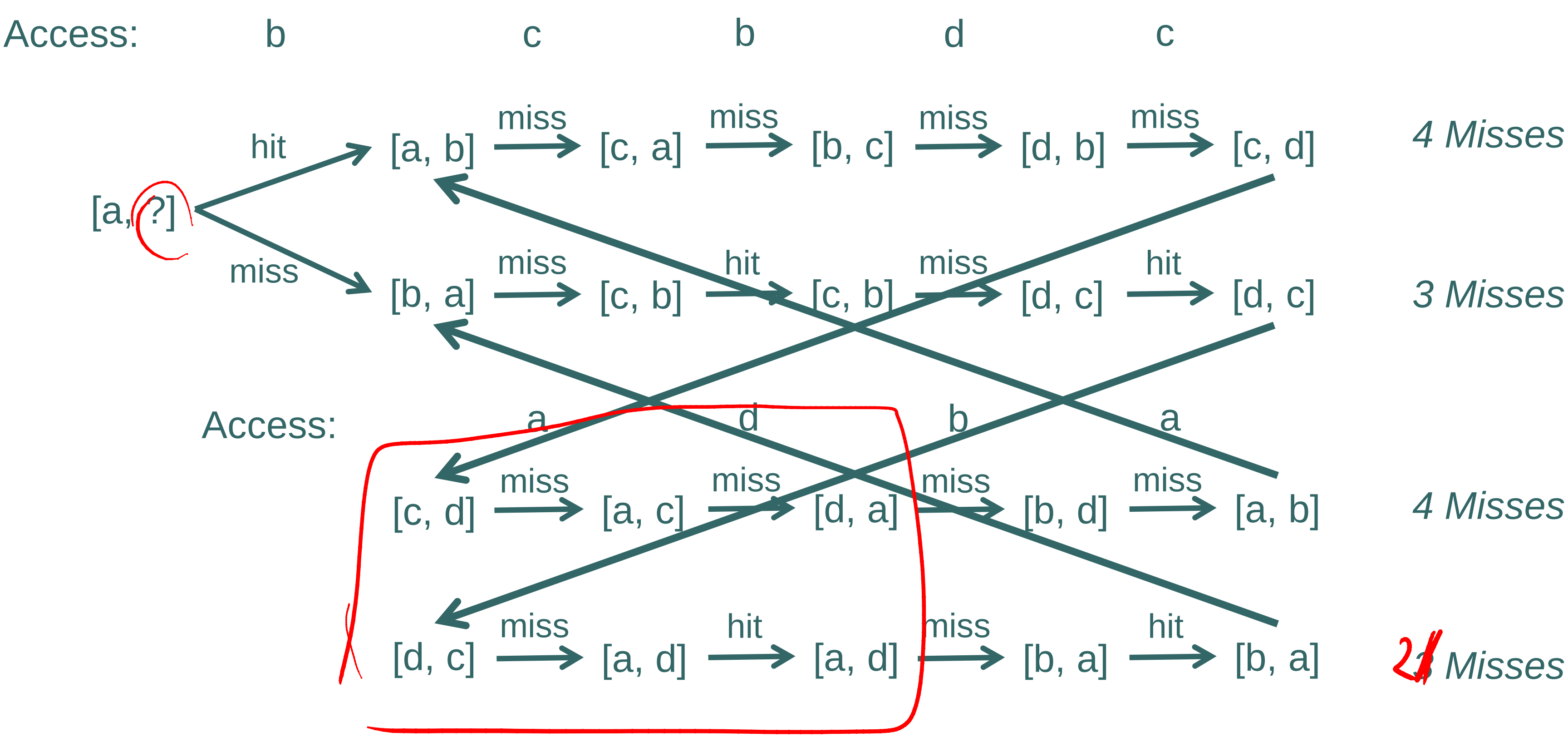
Domino Effects

- Intuitively:

  domino effect = “unbounded” timing anomaly

- Examples:
  - Pipeline (e.g. PowerPC 755)
  - Caches (FIFO, PLRU, MRU, …)

Domino Effects
Example: Cache Domino Effect of FIFO



Similar examples exist for PLRU and MRU.
Impossible for LRU.

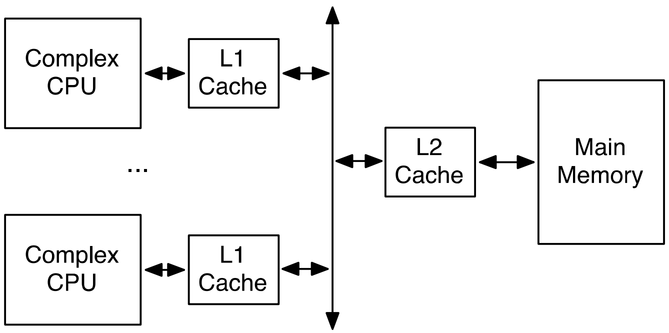
Domino Effects
Open Analysis and Design Challenges

Exactly as with timing anomalies:

- How to determine whether a given timing model exhibits domino effects?
- How to construct processors without domino effects?
- How to construct conservative timing model without domino effects?

Timing Compositionality Motivation

- Some timing accidents are hard or even impossible to statically exclude at any particular program point:
  - Interference on a shared bus: depends on behavior of tasks executed on other cores
  - Interference on a cache in preemptively scheduled systems
  - DRAM refreshes
- But it may be possible to make cumulative statements about the number of these accidents



Timing Compositionality
Intuitive Meaning

- Timing of a program can be decomposed into contributions by different “components”, e.g.
  - Pipeline
  - Cache non-preempted
  - Cache-related preemption delay
  - Bus interference
  - DRAM refreshes
  - …
- Example, decomposition into pipeline and cache

$$T_{pipeline,\ cache}(P, \langle p, c \rangle) \not\leq T_{pipeline}(P, \langle p \rangle) \oplus T_{cache}(P, \langle c \rangle)$$

Timing Compositionality
Application in Timing Analysis

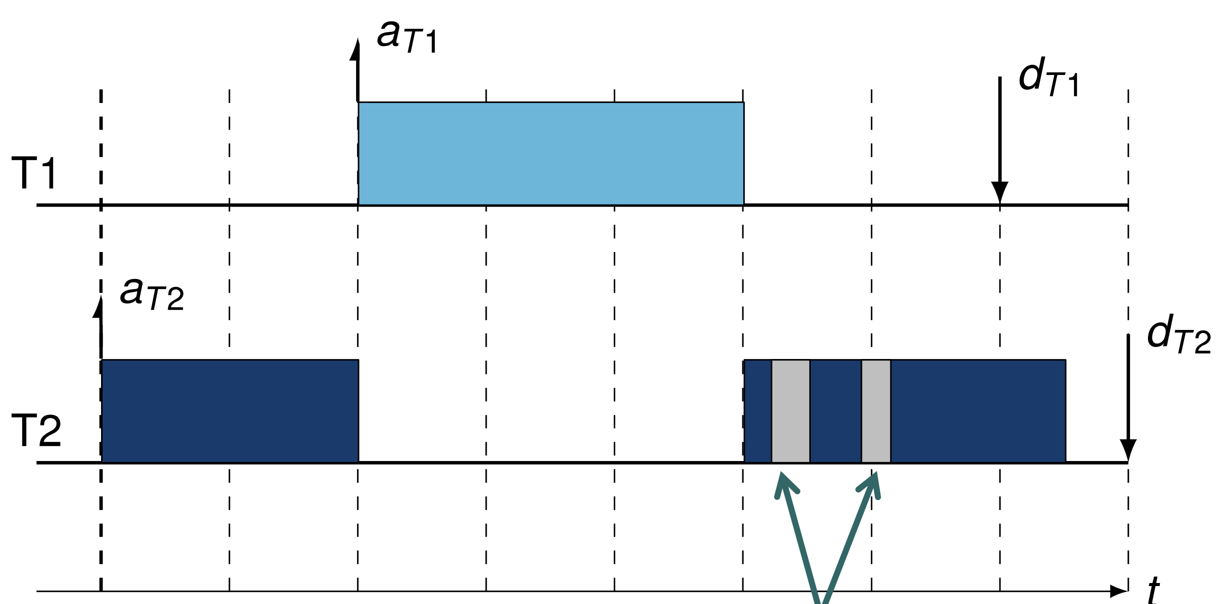
Then, the components (here: pipeline and cache) can also be analyzed separately:

$$
\begin{aligned}
WCET_{pipeline,\ cache}(P) &= \max_{p,c} T_{pipeline,\ cache}(P, \langle p, c \rangle) \\
&\leq \max_{p} T_{pipeline}(P, \langle p \rangle) \oplus \max_{c} T_{cache}(P, \langle c \rangle) \\
&= WCET_{pipeline}(P) + WCET_{cache}(P)
\end{aligned}
$$

Timing Compositionality

Example: “Cache-aware” Response-Time Analysis

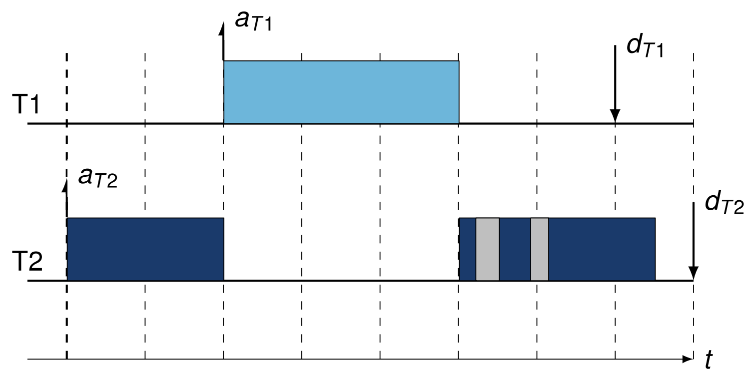
In preemptive scheduling, preempting tasks may “disturb” the cache contents of preempted tasks:



Additional misses due to preemption, referred to as the Cache-Related Preemption Delay (CRPD).

Timing Compositionality

Example: “Cache-aware” Response-Time Analysis



Timing decomposition:

- WCET of T1 without preemptions: C1
- WCET of T2 without preemptions: C2
- Additional cost of T1 preempting T2:

$$CRPD_{1,2} = BRT * \#additional\ misses$$

"BLOCK RELOAD TIME"

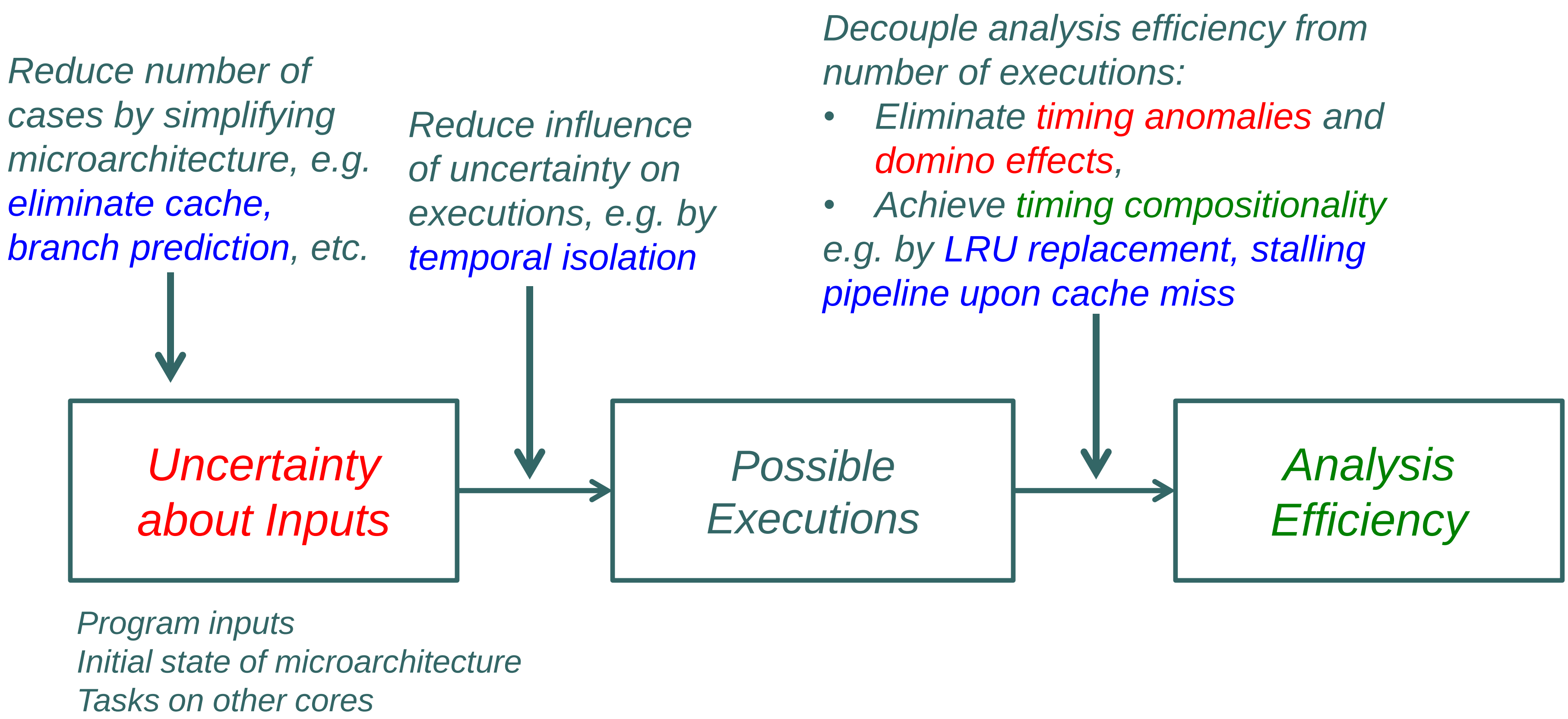
→ Response time of T2:

$$R2 \le C2 + \#preemptions \times (C1 + CRPD_{1,2})$$

Timing Compositionality
Open Analysis and Design Challenges

- How to check whether a given decomposition of a timing model is valid?
- How to compute bounds on the cost of individual events, such as cache misses (BRT in previous example) or bus stalls?
- How to build microarchitecture in a way that permits a sound and precise decomposition of its timing?

Summary:
Approaches to Increase Predictability



Summary

- (Fuzzy) notions of timing predictability
- Important related notions:
  - Timing anomalies
  - Domino effects
  - Timing compositionality
  - Temporal isolation
- Two ways of increasing predictability:
  1. Reduce uncertainty
  2. Reduce influence of uncertainty