Operating System Practice

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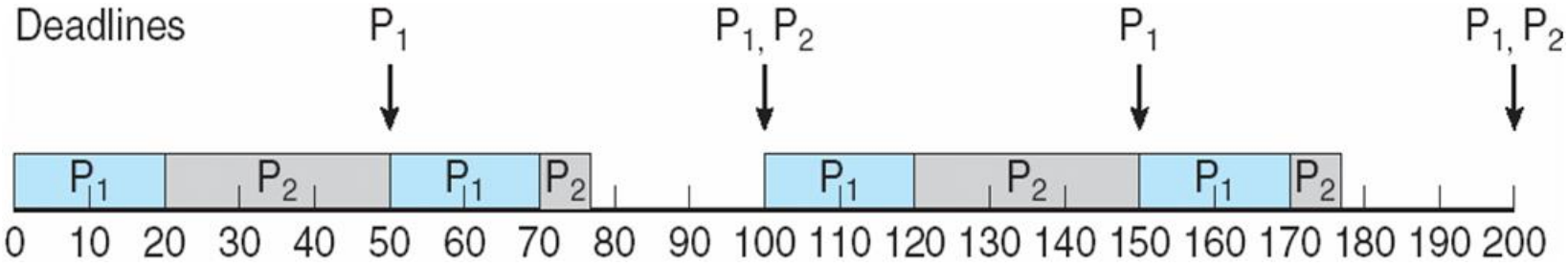
Worst-Case Execution Time (WCET) Analysis

Recall the Rate Monotonic Real-Time Scheduling

- A static priority is assigned to each task based on the inverse of its period
  - A task with shorter period ➔ higher priority
  - A task with longer period ➔ lower priority
  - For example:
    - P_1 has its period 50 and execution time 20
    - P_2 has its period 100 and execution time 37

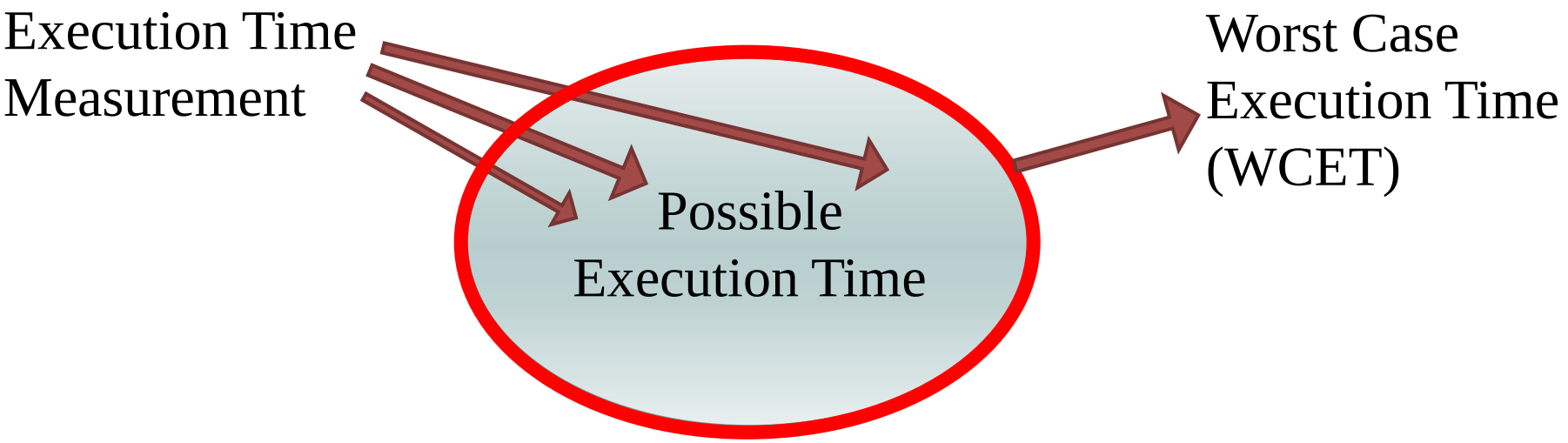
    ➔P_1 is assigned a higher priority than P_2

How can we get the EXECUTION TIME



Execution Time of a Program

- The execution time of a program might not be a constant



WCETs are most essential assumptions for schedulability analysis

How to get the WCET of a program!?

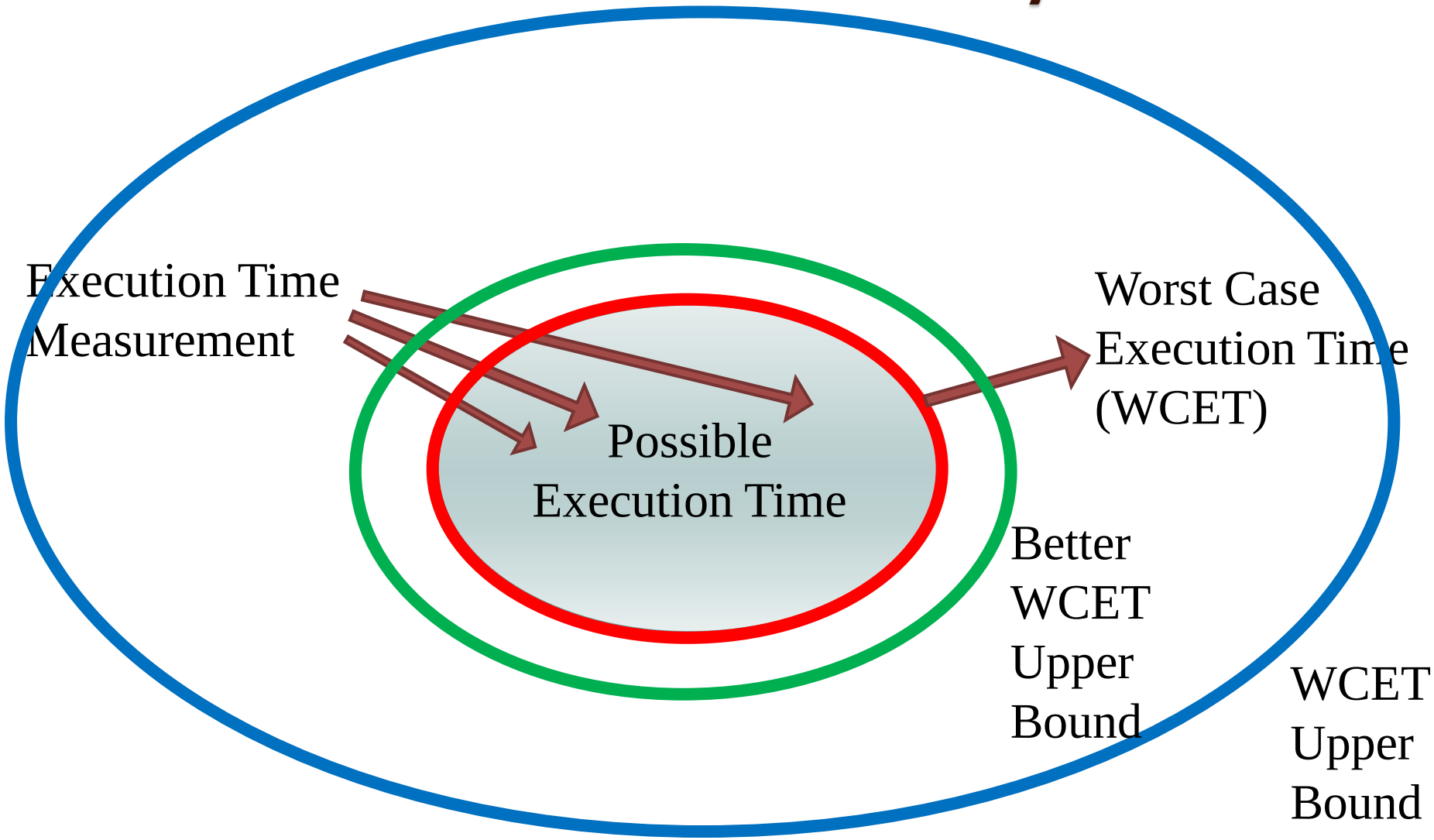
Factors for WCET Analysis

- Input parameters
  - Algorithm parameters
  - Problem size
- States of the system
  - Cache configuration, cache replacement policies
  - Pipeline configuration
  - Speculations
- Interferences from the environment
  - Scheduling policies
  - Interrupts

WCET Analysis

- Can we always get the WCET of a program?
  - Halting Problem tells us that we can not use an algorithm to decide whether another algorithm *m* halts on a specific input *x*.
  - Thus, WCET is also undecidable
- Most of industry's best practice
  - Measure it: determine WCET directly by running or simulating a set of inputs.
  - Exhaustive execution: by considering the set of all the possible inputs
- Another approach: compute an upper bound of the WCET
  - It should be no less than the WCET
  - It should be close to the WCET
  - It can not always be tight

Research of WCET Analysis



Challenges of Analyzing WCET

- Execution time $e(i)$ of machine instruction i
  - $e(i)$ is not a constant
  - The (architectural) execution state s should be considered
  - Thus, $e(i)$ is within the following range

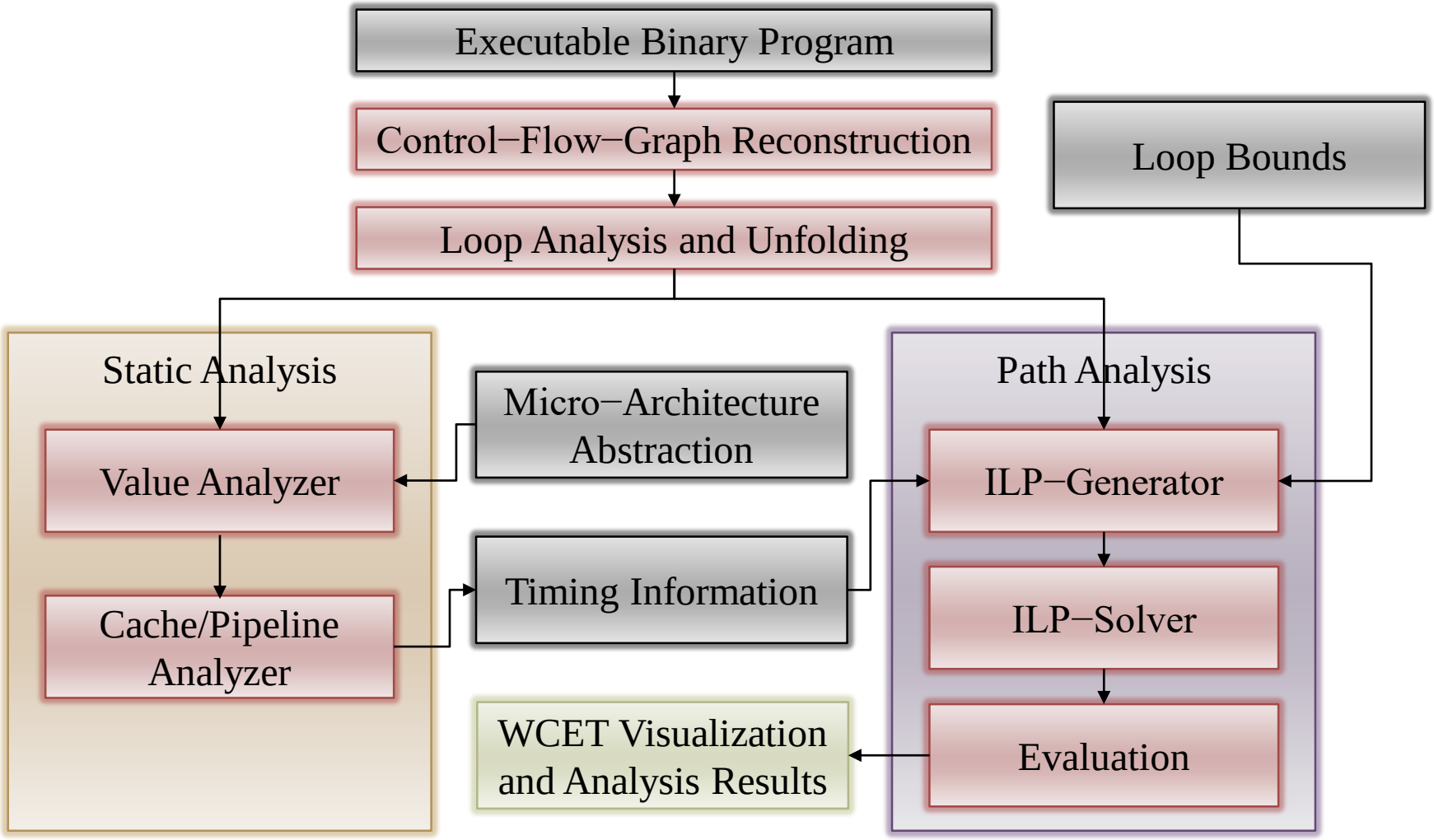
    $\min\{e(i, s)|s \in S\} \leq e(i) \leq \max\{e(i, s)|s \in S\}$,

    where S is the set of all states
- Using $\max\{e(i, s)|s \in S\}$ as the upper bound of WCET
  - It is safe
  - But it might be not tight

Timing Accidents and Penalties

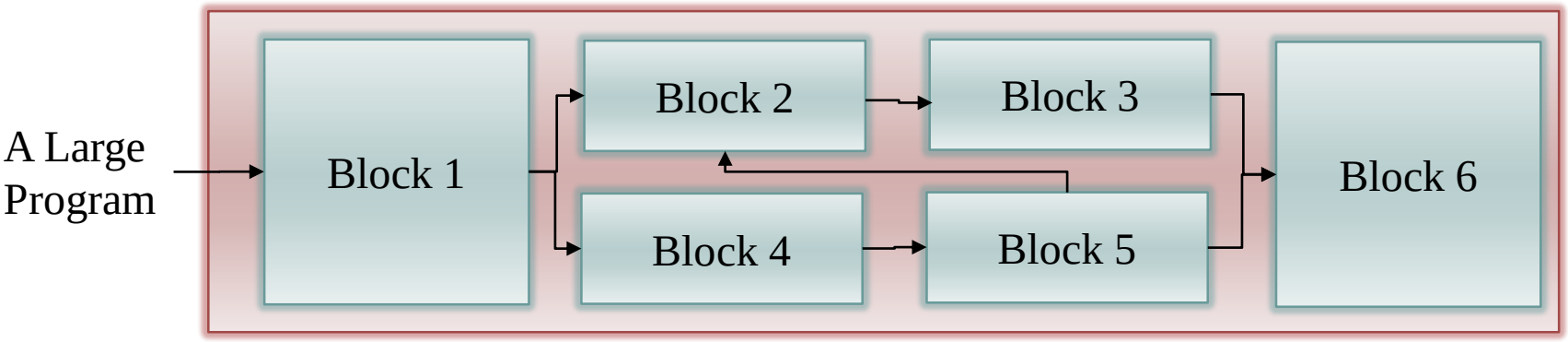
- Timing Accident: cause for an increase of the execution time of an instruction
- Timing Penalty: the associated increase
- Types of timing accidents
  - Cache misses
  - TLB misses
  - Page faults
  - Pipeline stalls
  - Branch prediction errors
  - Bus collisions

Overall Structure of WCET Analisis



Basic Blocks

- Beginning of Basic Blocks
  - The first instruction
  - The targets of un/conditional jumps
- Ending of Basic Block
  - The basic block consists of the block beginning and runs until the next block beginning (exclusive) or until the program ends



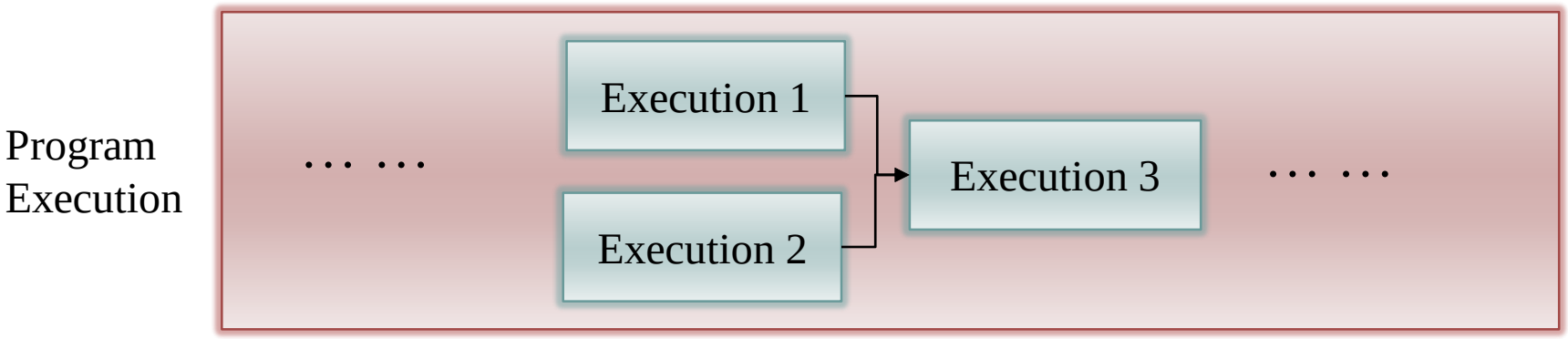
Value Analysis

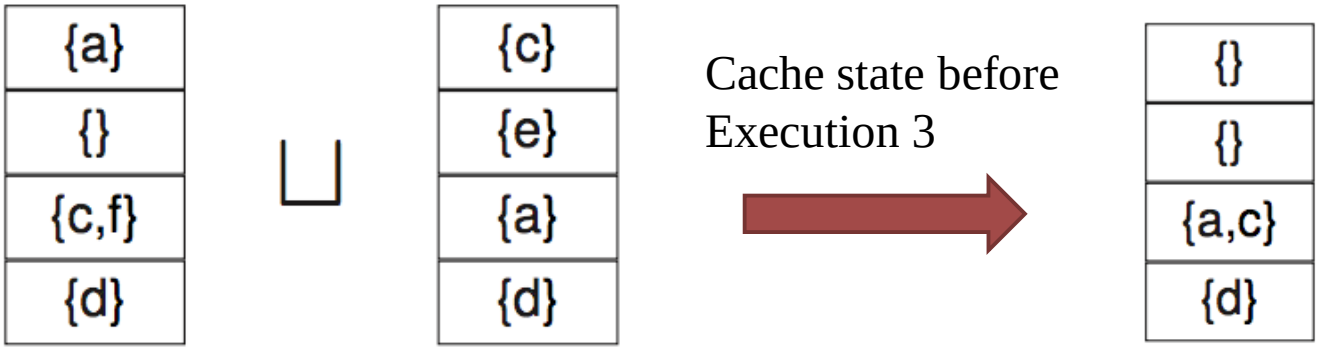
- Motivation
  - Provide access information to data-cache/pipeline analysis
  - Detect infeasible paths
  - Derive loop bounds
- Method
  - Calculate intervals at all program points
  - Consider addresses, register contents, local/global variables
- Abstract Interpretation
  - Perform the program's computation using value descriptions or abstract values in place of the concrete values

Abstract Interpretation

- Abstract Domain
  - Replace an integer/double operator by using intervals
  - For example, L = [3,5] stands for L is a value between 3 and 5
- Abstract Transfer
  - For example, operator +: [3, 5] + [2, 6] = [5, 11]
  - For example, operator −: [3, 5] − [2, 6] = [-3, 3]
- Join Combining
  - For example, [a, b] join [c, d] becomes [min{a, c}, max{b, d}]
  - That is, [3, 5] join [2, 4] becomes [2, 5]

A Case Study with LRU: Join Management





Pipelines

- An instruction execution consists of several sequential phases, e.g.,
  - Fetch
  - Decode
  - Execute
  - Write Back

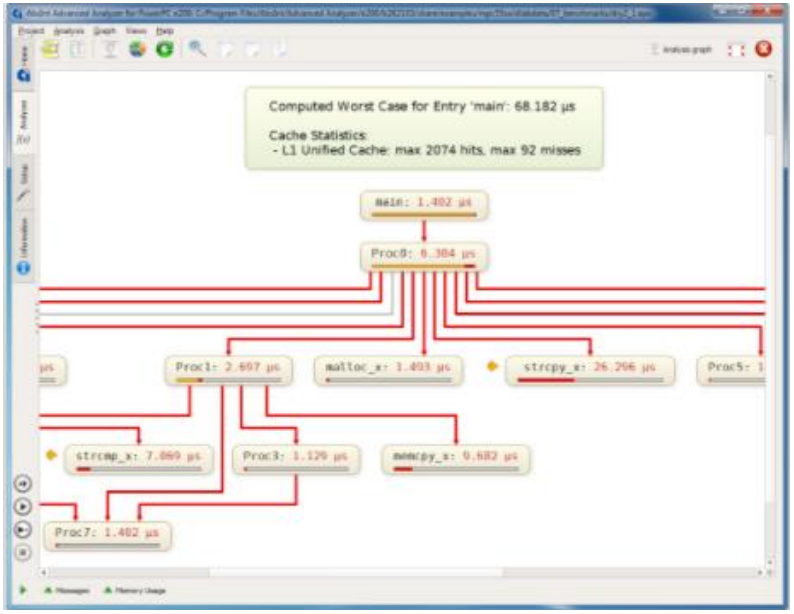
Inst 1	Inst 2	Inst 3	Inst 4
Fetch			
Decode	Fetch		
Execute	Decode	Fetch	
Write Back	Execute	Decode	Fetch
	Write Back	Execute	Decode
		Write Back	Execute
			Write Back

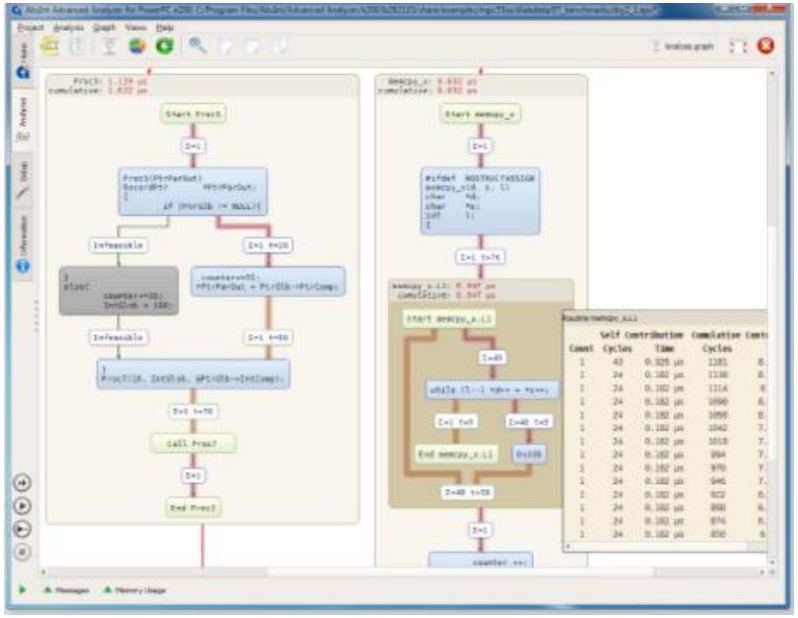
Hardware Features of Pipelines

- Instruction execution is split into several stages
- Several instructions can be executed in parallel
- Some pipelines can start more than one instruction per cycle: VLIW, Superscalar
- Some CPUs can execute instructions out-of-order
- Practical Problems: Hazards and cache misses
  - Data Hazards: Operands not yet available (Data Dependences)
  - Control Hazards: Conditional branch
  - Resource Hazards: Consecutive instructions use same resource
  - Instruction-Cache Hazards: Instruction fetch causes cache miss

WCET Analysis Tools (1 / 2)

- aiT WCET Analyzers

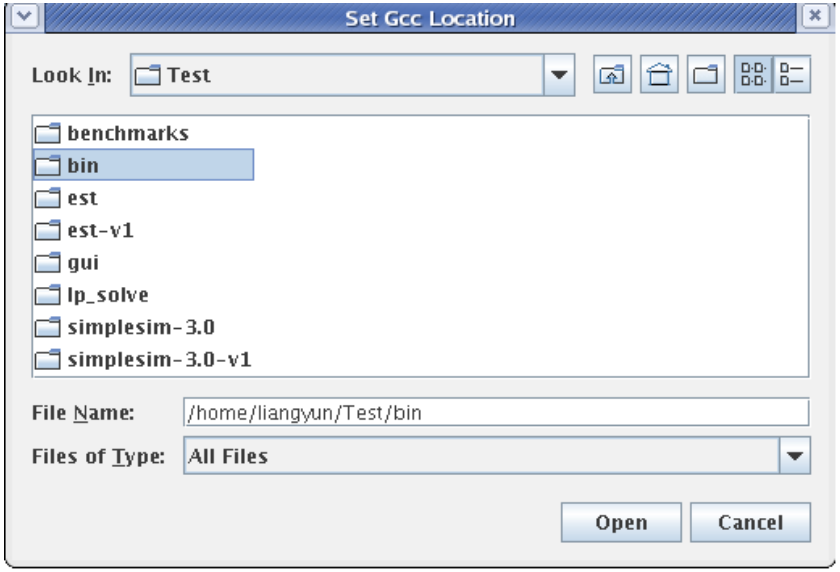


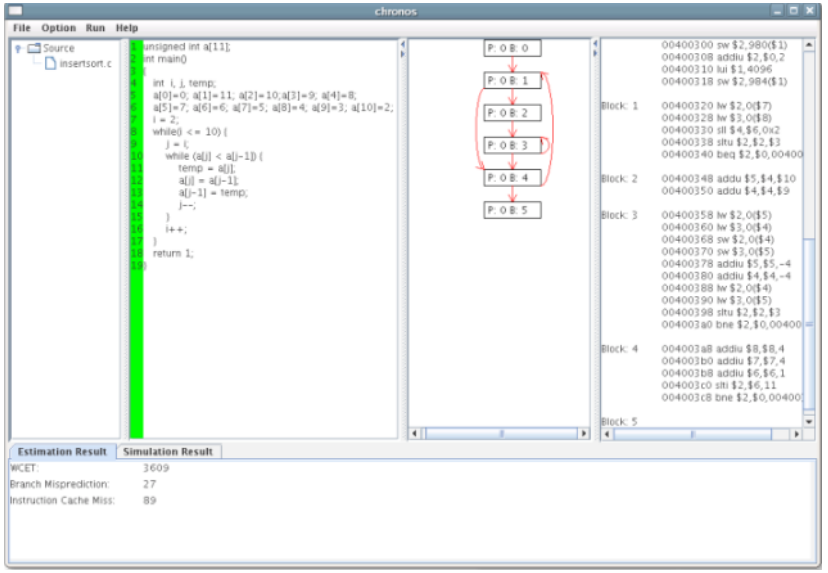


- It is not free
- https://www.absint.com/ait/

WCET Analysis Tools (2/2)

- Chronos





- It is free and open-source for academic
- But it is not stable
- http://www.comp.nus.edu.sg/~rpembed/chronos/