Embedded Operating Systems

Che-Wei Chang

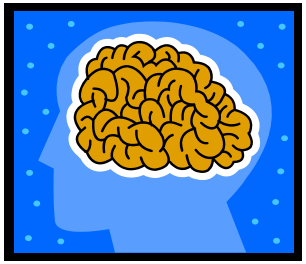
chewei@mail.cgu.edu.tw

Department of Computer Science and Information Engineering, Chang Gung University

Course Roadmap

Basic Concepts

- Embedded System Design Concepts
- Embedded System Developing Tools and Operating Systems
- Embedded Linux and Android Environment



Core Technology

- Real-Time System Design and Scheduling Algorithms
- System Synchronization Protocols

Real Implementation

- System Initialization and Memory Management
- Power Management Techniques and System Routine
- Embedded Linux Labs and Exercises on Android

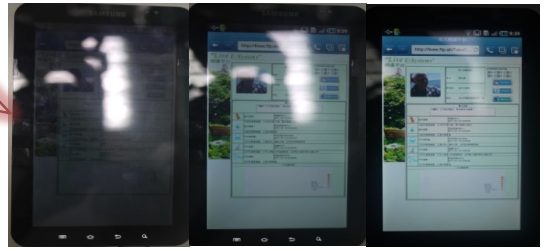
Real-Time Scheduling II

Energy Saving Designs

Two Approaches to Reduce the Power Consumption of Devices

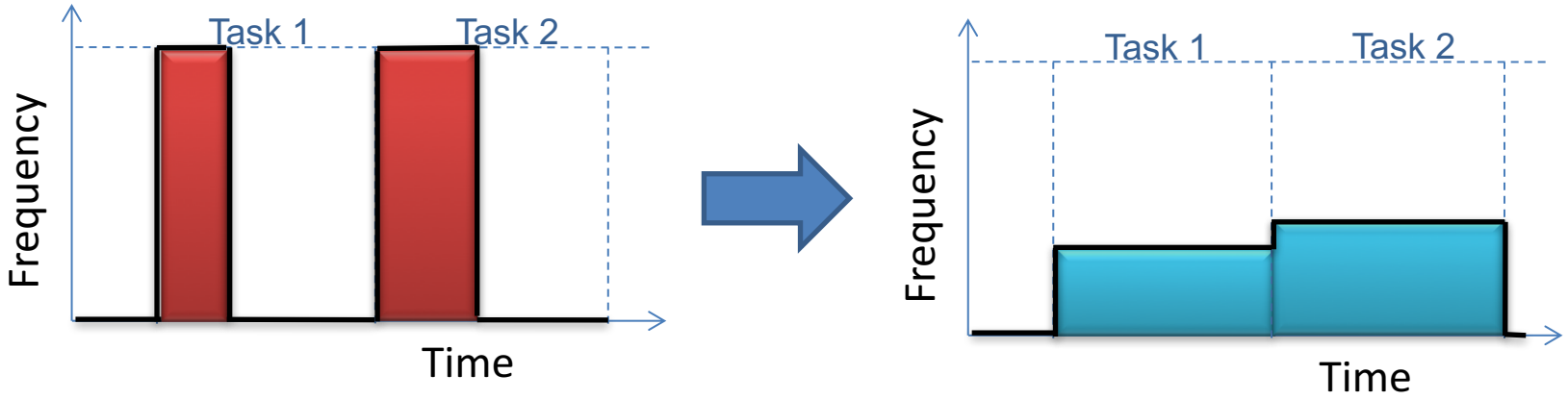
- Dynamic Voltage and Frequency Scaling (DVFS)
  - Scale down the voltage and/or frequency to reduce the processor power consumption
  - An example: reducing 17% of the energy consumption for H.264 decoding over TI DaVince DM6446
- Dynamic Power Management (DPM)
  - Change to an energy-efficient state to reduce the power consumption of peripheral devices
  - An example: reducing 15% of the energy consumption for the browser over Android Galaxy Tab

Power Consumption	1625mW	2023mW	3166mW

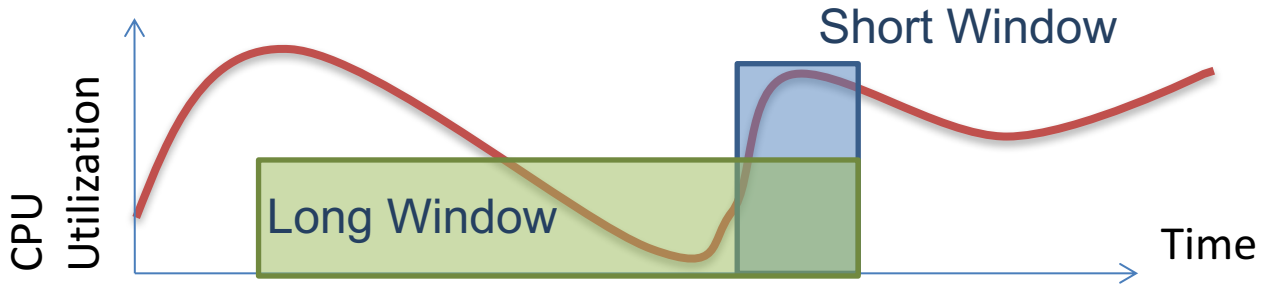


Dynamic Frequency and Voltage Scaling Designs

- The Observation: It is energy-efficient to scale down the processor frequency dynamically to fit current workloads



- The Approach: It keeps a window or buffer to estimate the workload



Energy-Efficient Multimedia Platforms

- Energy-Efficient ARM-DSP Platforms for H.264 Decoding
  - Analyze the workload variance of multimedia jobs
  - Take real platforms for an ARM+DSP design
  - Achieve more than 17% energy saving for the ITRI PAC SoC

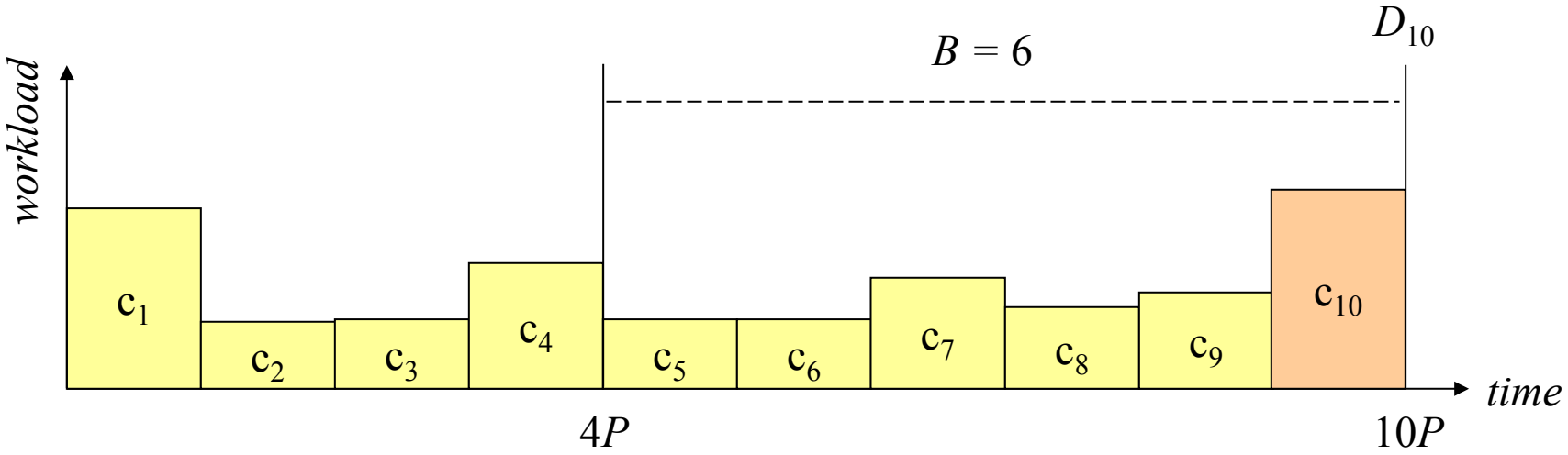
Implementation on a PC with Phenom II

Implementation on an Android Phone

Implementation on the PAC Soc

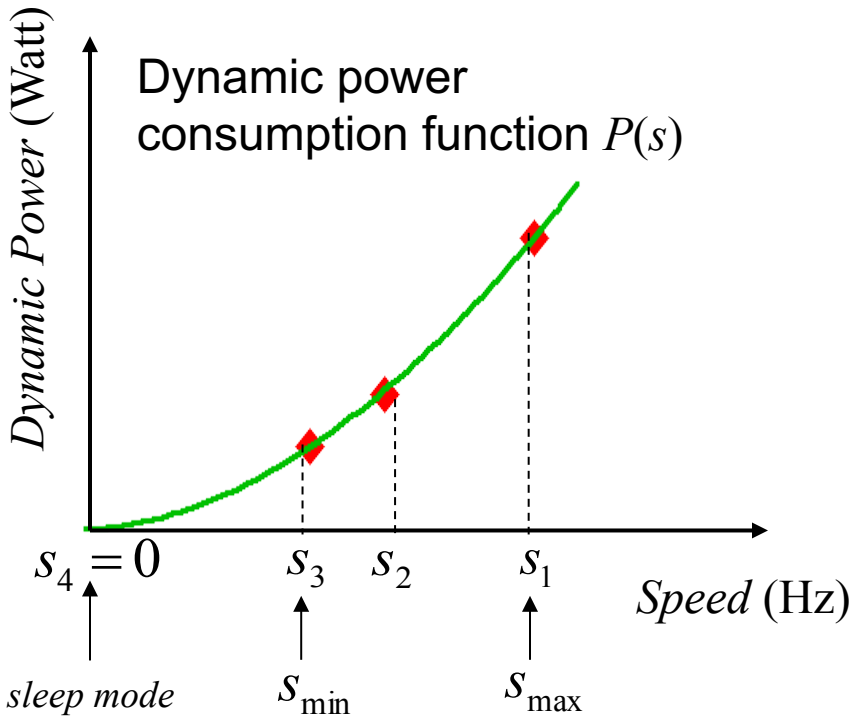
Examples of Energy Saving Designs

Task Model of Multimedia Applications



- A task consists of a sequence of jobs
- Jobs arrive by a period: P time units
- The workload of future job can be predicted based on the log
- Because of the buffer size limitation, the number of pending jobs at any time point is bounded by a fixed integer B

Processor Power Model



$$P(s) = C_{ef} V_{dd}^{\ 2} s,$$

$$s = k \frac{(V_{dd} - V_t)^2}{V_{dd}}$$

where

C_{ef} is the effective switch capacitance

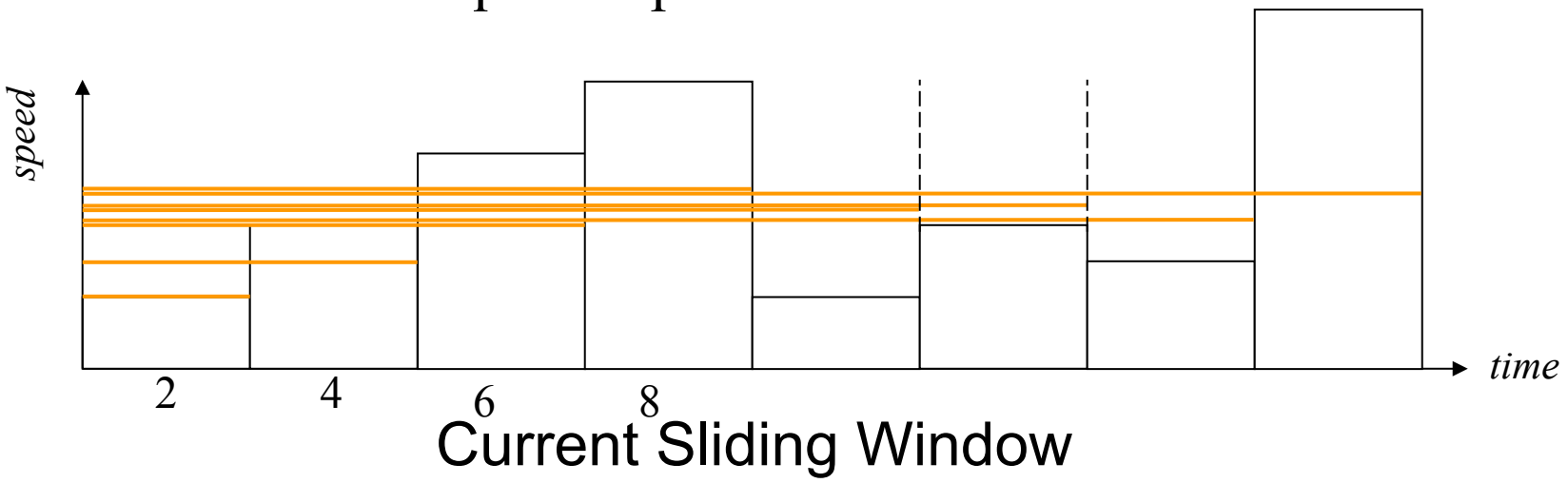
V_t is the threshold voltage

V_{dd} is the supply voltage

k is a hardware-design-specific constant

Concepts of DVFS Algorithm

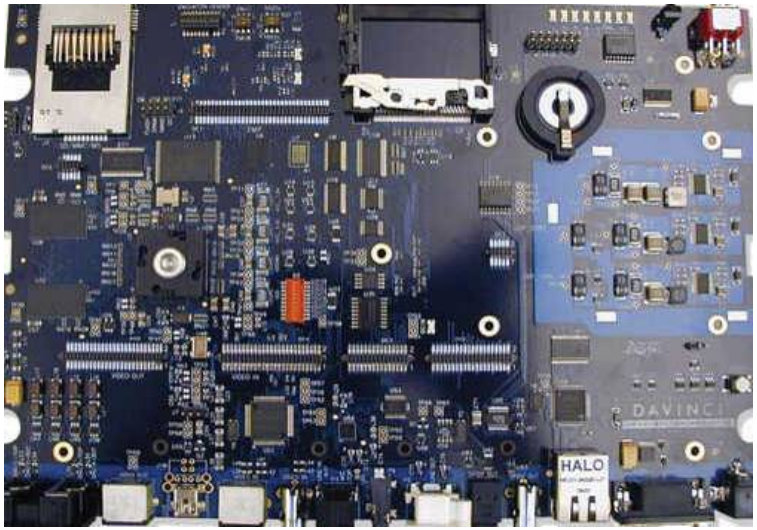
- An Energy-Efficient Multimedia Application
  - ➔Make the frequency as low as possible
  - ➔Meet all performance constraints
  - ➔Find the critical (most demanding) interval by calculating the maximum required speed in all intervals



Hardware Platform

- Platform: Texas Instruments DaVinci DVEVM (The Digital Video Evaluation Module)

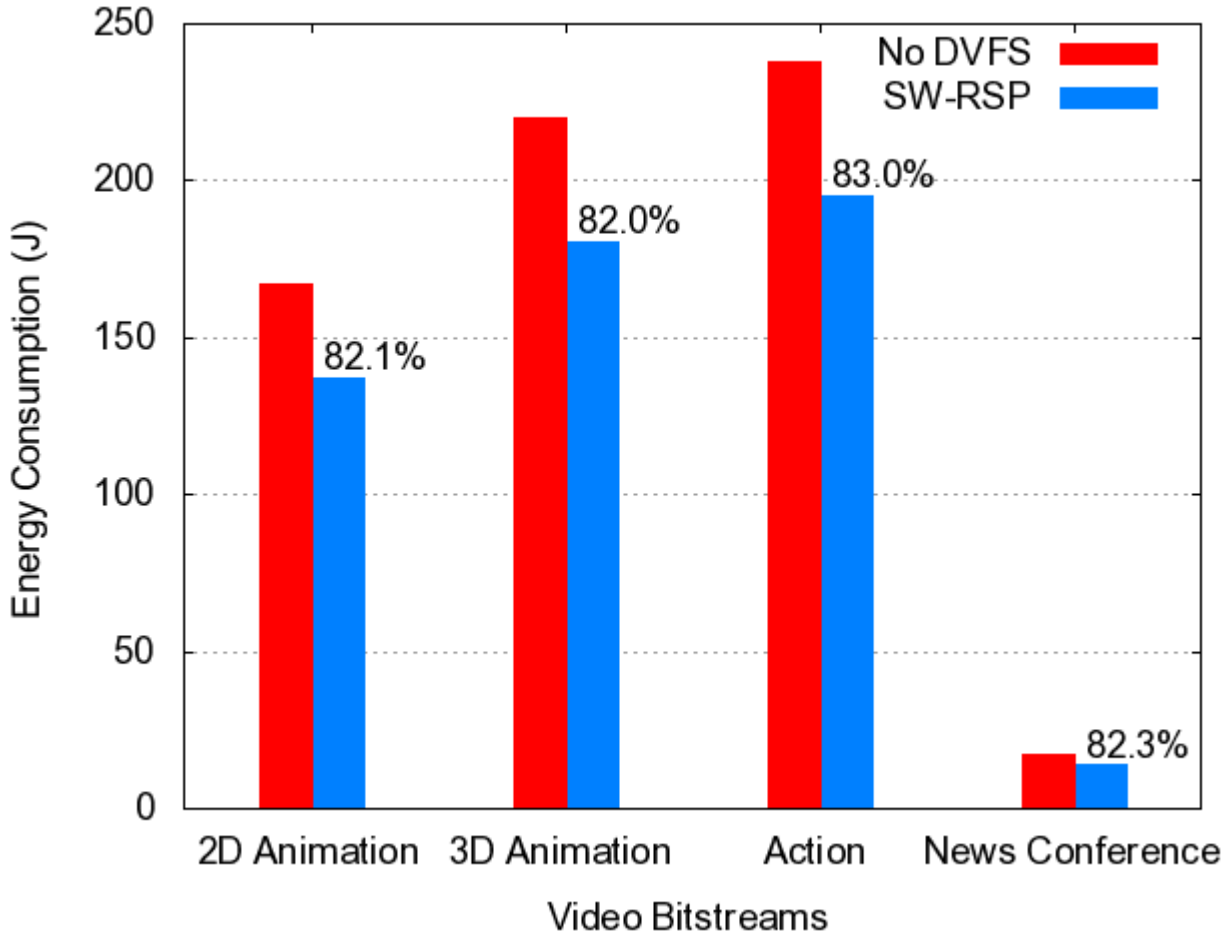
Speed Mode	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
Frequency (MHz)	594	567	540	513	486	459	432	405	0



Input Video Streams

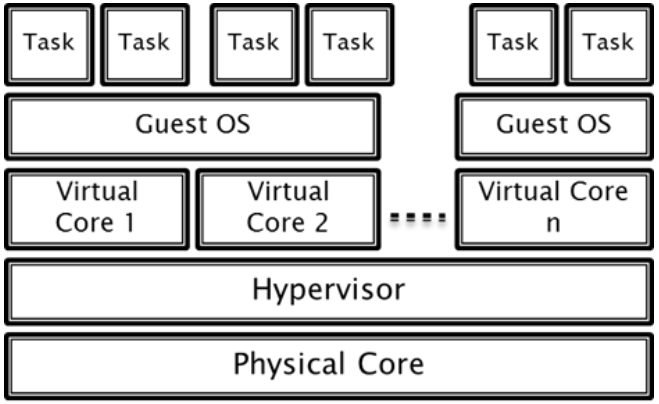
	2D Animation	3D Animation	Action	News Conf.
				
Number of frames	17985	19182	19182	1751
FPS	29.97	29.97	23.98	23.98
Bit-rate (kbps)	754.99	1237.58	1798.87	631.27
PSNR	42.44	41.85	40.04	42.49
Resolution	720×480	720×480	720×480	720×480

Experimental Results

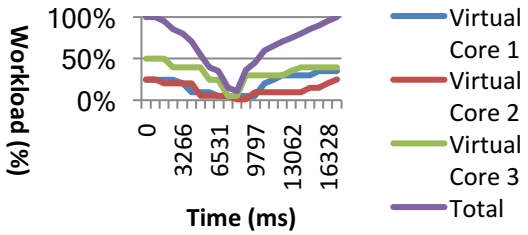


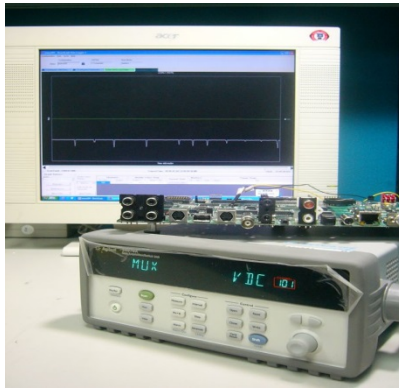
Energy-Efficient Virtual Cores

- A Virtual Core
  - A sporadic server in hypervisor's view
  - An individual core for user applications
- Energy-Efficient Virtualization*
  - Approximation bound analysis
  - A real implementation on ARM 9 with L4 microkernel with DVFS supports

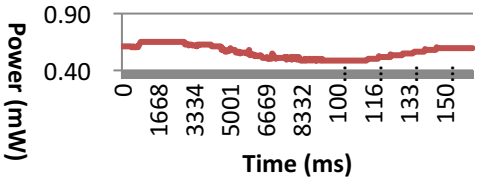


The Workloads of Virtual Cores





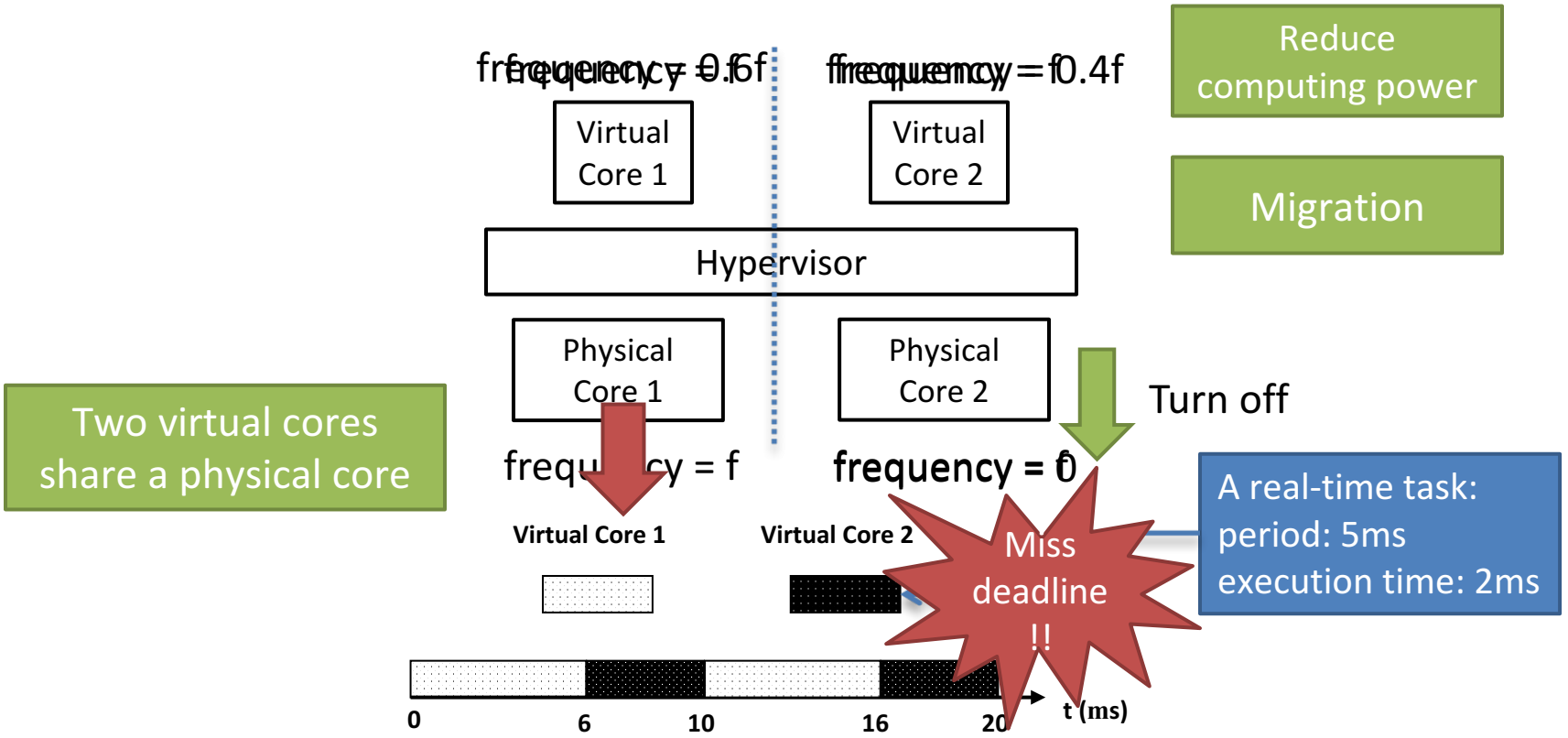
The Power Trace of the System



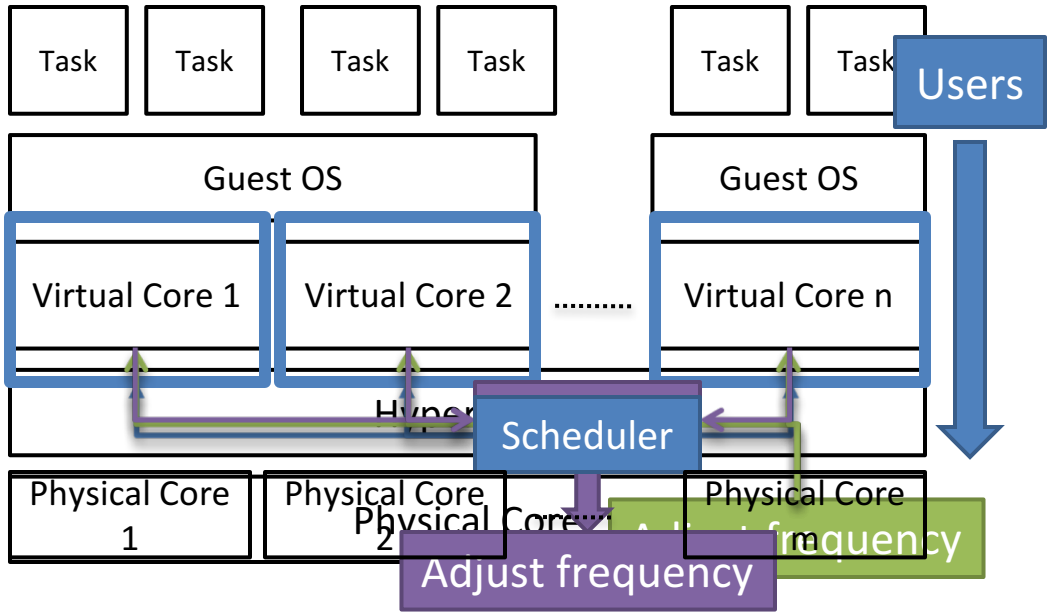
* Yu-Chia Lin, Chuan-Yue Yang, Che-Wei Chang, Yuan-Hao Chang, Tei-Wei Kuo and Chi-Sheng Shih, "Energy-Efficient Mapping Technique for Virtual Cores," in ECRTS. 6-9, 2010.

Virtual Multi-Core Scheduling

- The significant growing on the number of cores per system
- The consideration of the DVS functionality in virtual cores

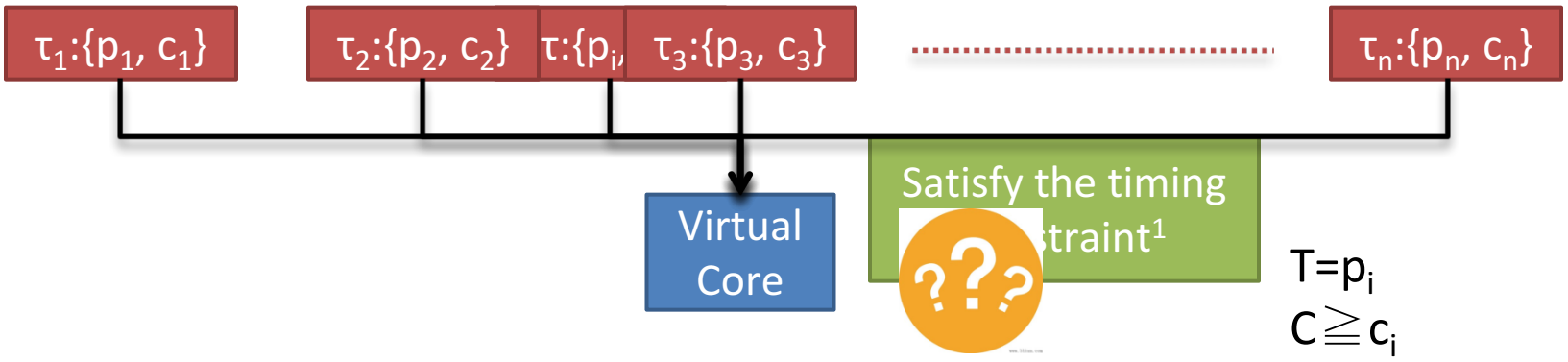


Power-Aware Virtualization System



- Virtual core model
- Hypervisor functionalities
  - Minimize the energy consumption
  - Manage virtual cores with virtual core functions
  - Guarantee the needs of each virtual cores

Virtual Core Model – Real Time Constraint



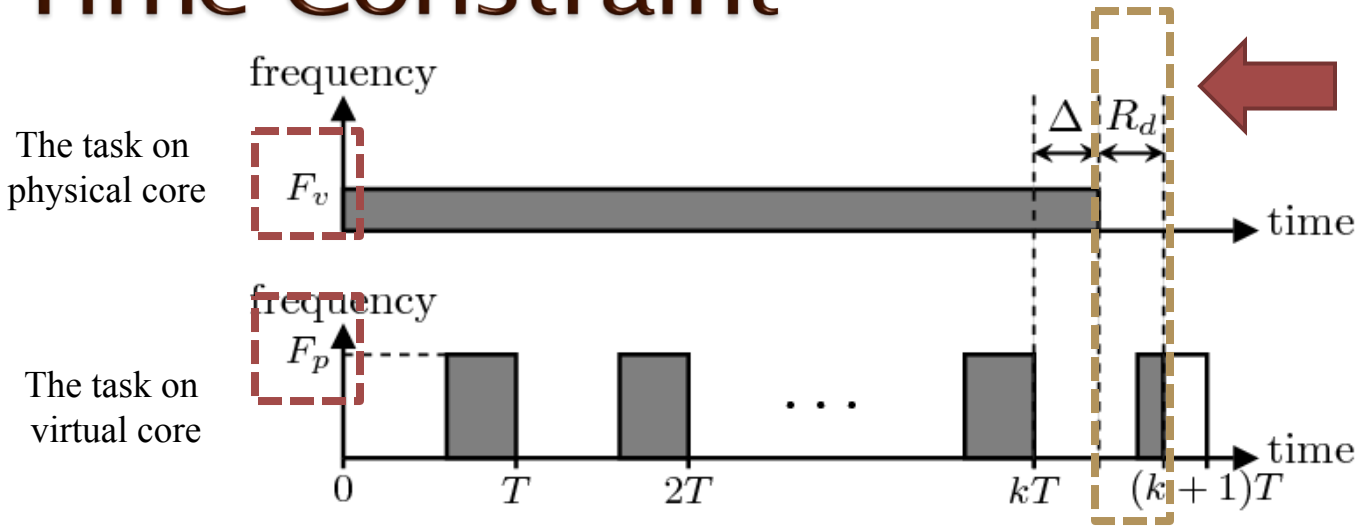
- Given a set of real-time tasks $\{\tau_1, \tau_2, \ldots, \tau_n\}$, the timing constraints of these tasks can be met with a virtual core by setting

$$T = \gcd(p_1, p_2, \ldots, p_n) \quad \& \quad C \geq \sum_{i=1}^{n} \frac{c_i}{p_i} \times T$$

if the real-time tasks are scheduled under the Earliest-Deadline-First (EDF) scheduling policy

For k=1, 2, …, n $C_k = \left\lfloor \frac{p_k}{T} \right\rfloor C = \frac{p_k}{T} C \geq p_k \sum_{i=1}^{n} \frac{c_i}{p_i}$

Virtual Core Model – Response-Time Constraint



Where is the boundary

- Given a tolerable response time delay σ, the delay of the response time on the virtual core can be no more than σ if

$$T \le \frac{\sigma}{1 - F_v / F_p} \quad \& \quad C \ge F_v \cdot T$$

$$R_d = (T - \frac{C}{F_p}) + \frac{\Delta \cdot F_v}{F_p} - \Delta$$

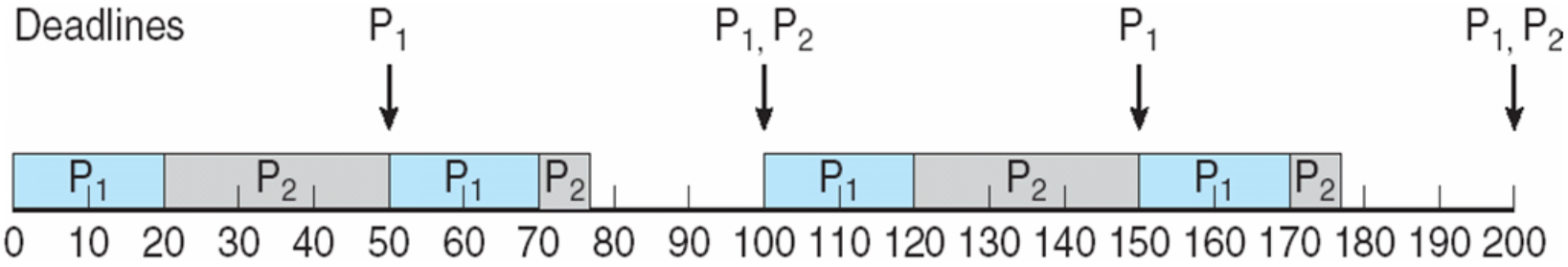
Worst-Case Execution Time (WCET) Analysis

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

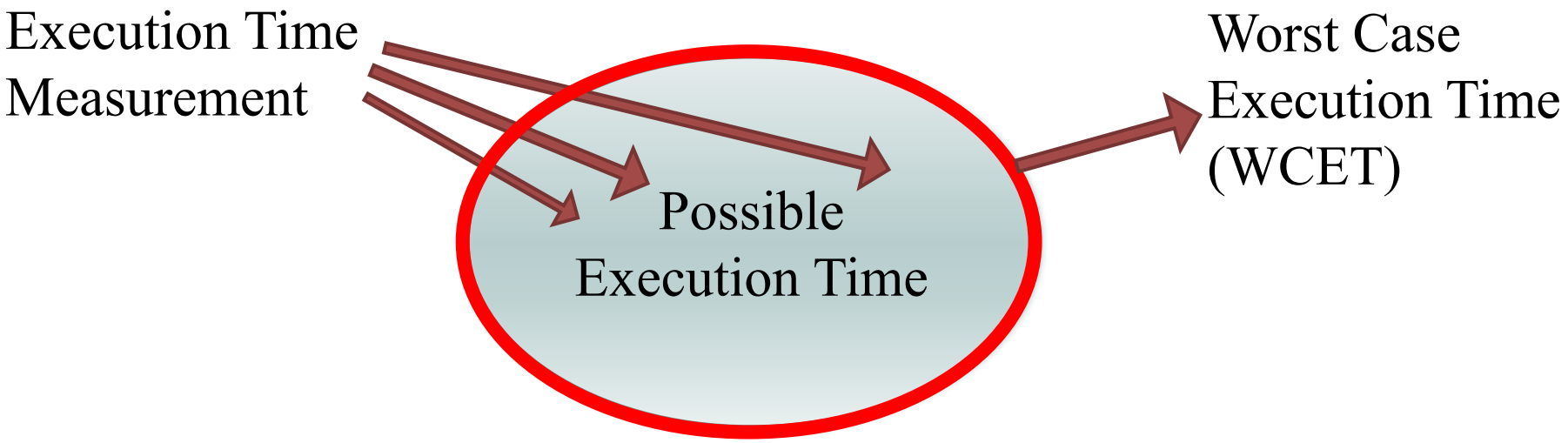
    ➔P_1 is assigned a higher priority than P_2

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!?

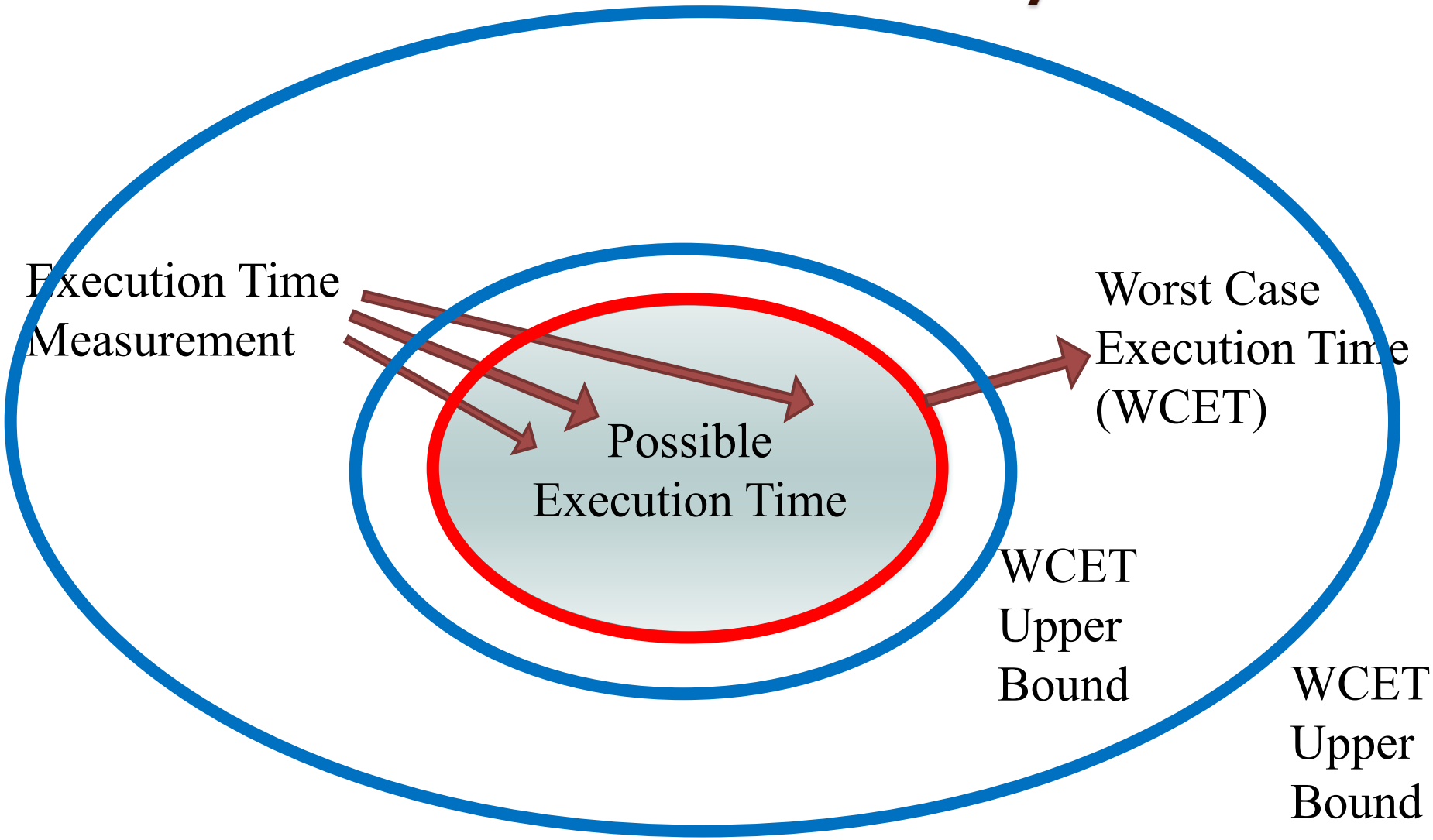
Factors for WCET Analysis

- 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

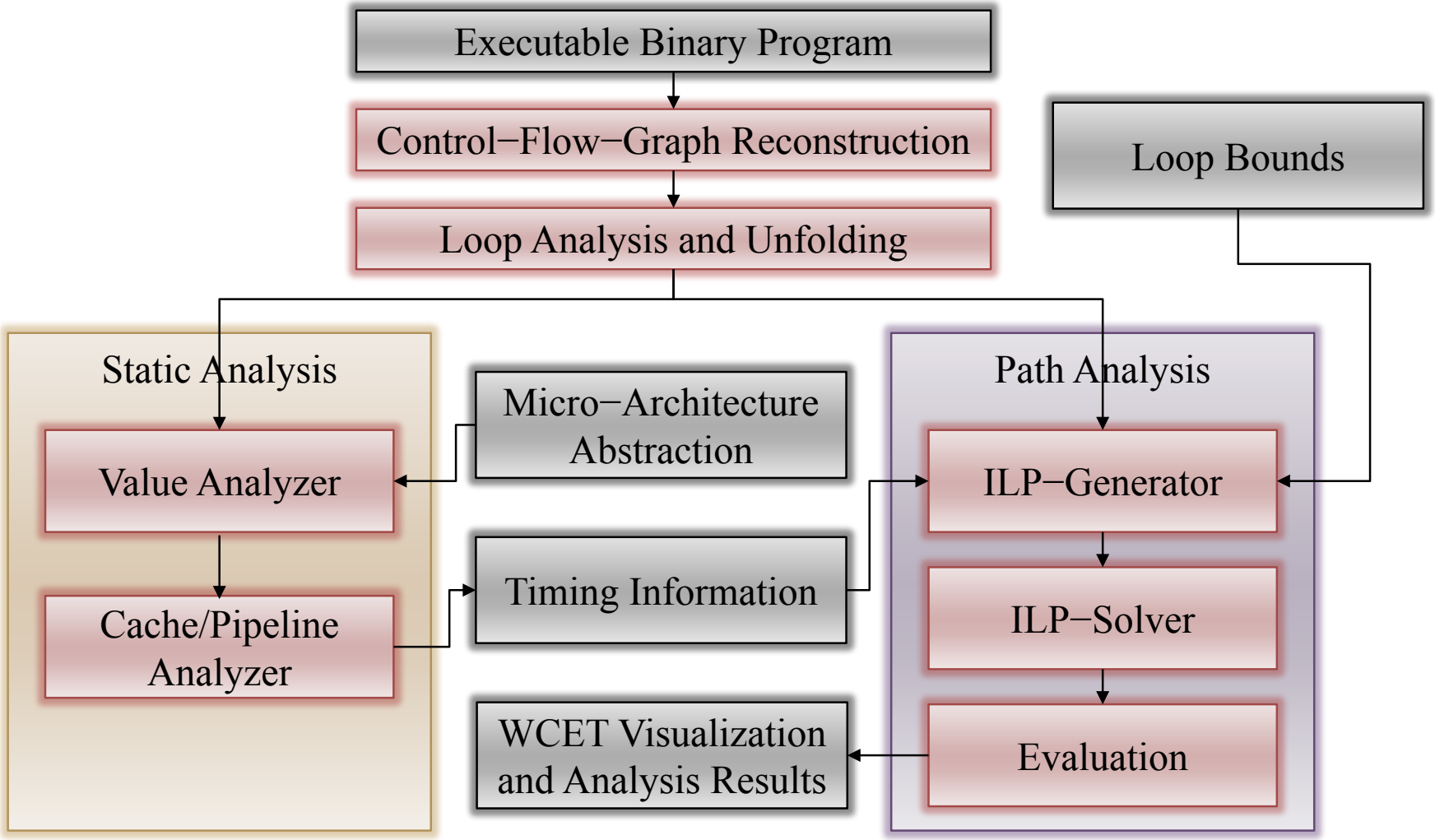
  $$\min\{e(i, s)|s \in S\} \leq e(i) \leq \max\{e(i, s)|s \in S\},$$

  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

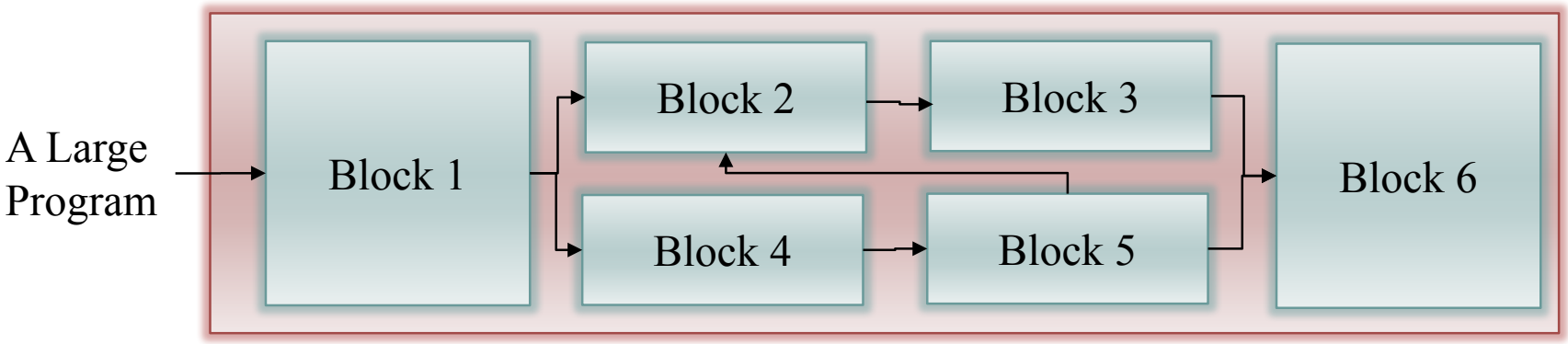
- Timing Accident: cause for an increase of the execution time of an instruction
- Timing Penalty: the associated increase
- Types of timing accidents
  - Cache misses
  - TLB misses
  - Page faults
  - Pipeline stalls
  - Branch prediction errors
  - Bus collisions

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

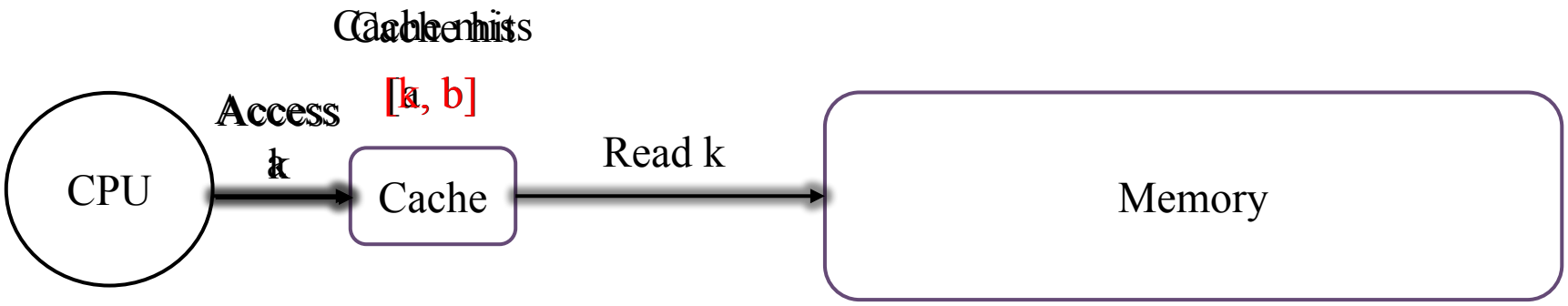
- Motivation
  - Provide access information to data-cache/pipeline analysis
  - Detect infeasible paths
  - Derive loop bounds
- Method
  - Calculate intervals at all program points
  - Consider addresses, register contents, local/global variables
- Abstract Interpretation
  - Perform the program's computation 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]

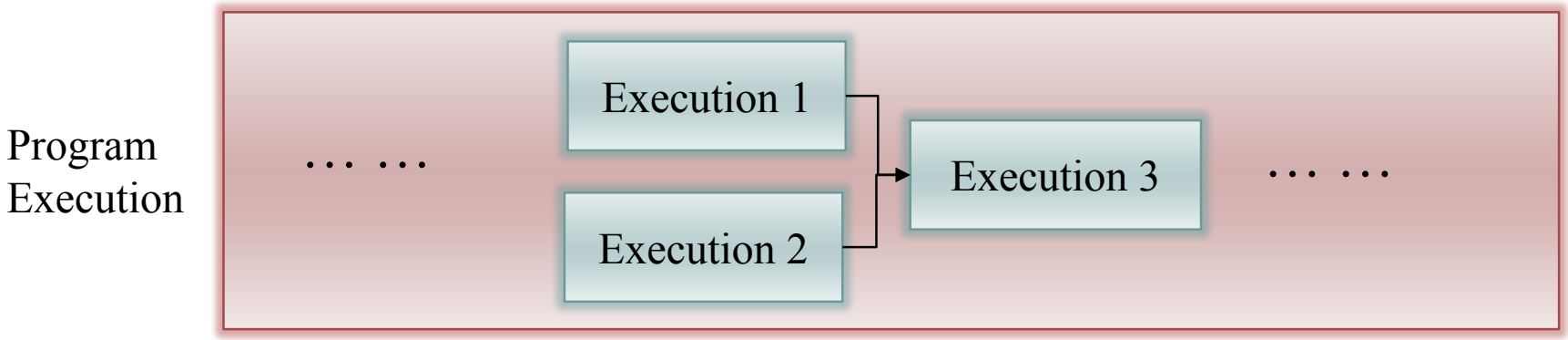
Cache Analysis

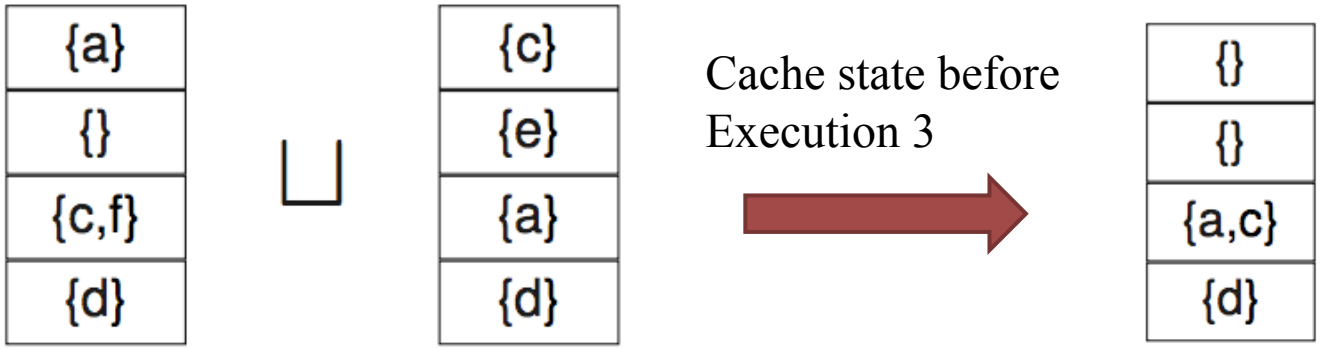
- How does it work:
  - Analyzed dynamically
  - Managed by replacement policies



- Why does it work:
  - Spatial locality
  - Temporal locality

A Case Study with LRU: Join Management





Pipelines

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

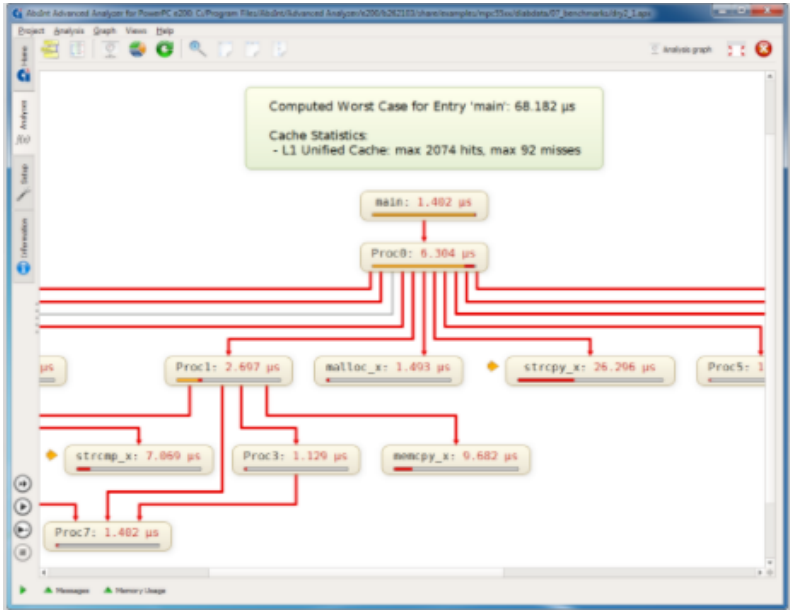
Inst 1	Inst 2	Inst 3	Inst 4
Fetch			
Decode	Fetch		
Execute	Decode	Fetch	
Write Back	Execute	Decode	Fetch
	Write Back	Execute	Decode
		Write Back	Execute
			Write Back

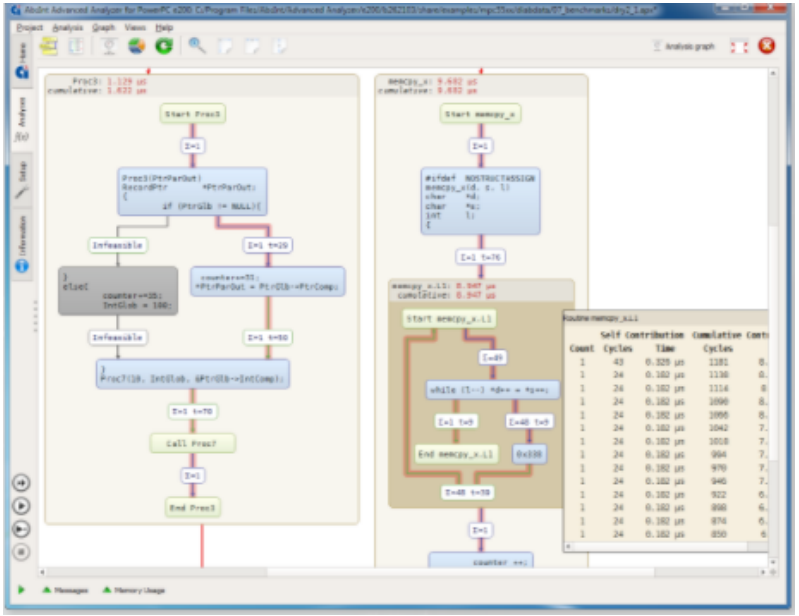
Hardware Features of Pipelines

- 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

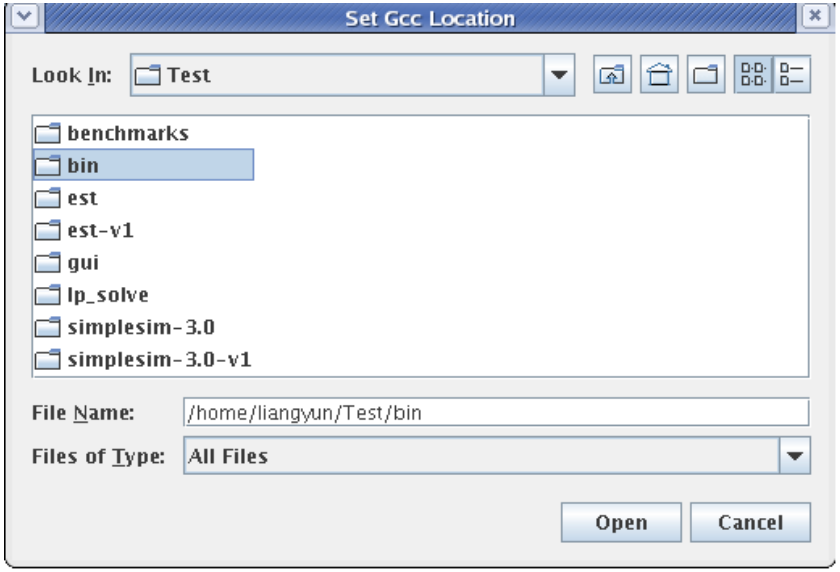


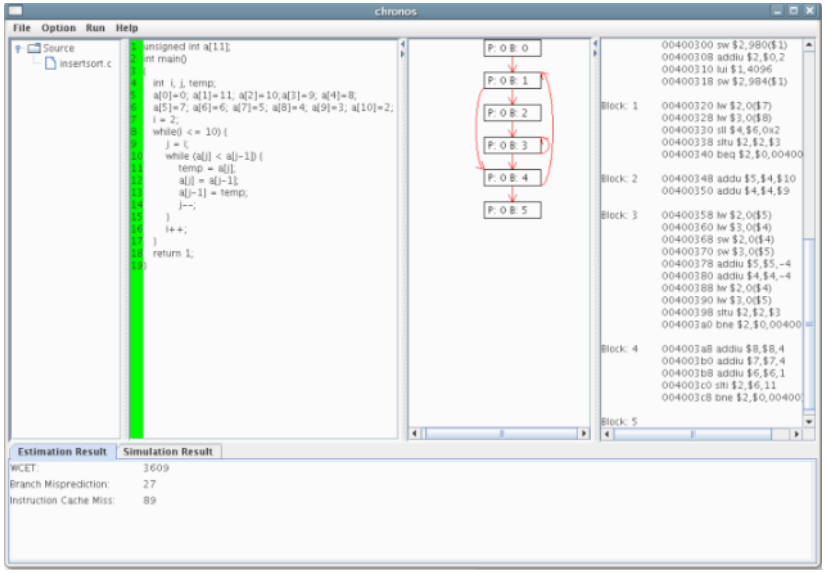


- It is not free
- https://www.absint.com/ait/

WCET Analysis Tools (1/2)

- Chronos



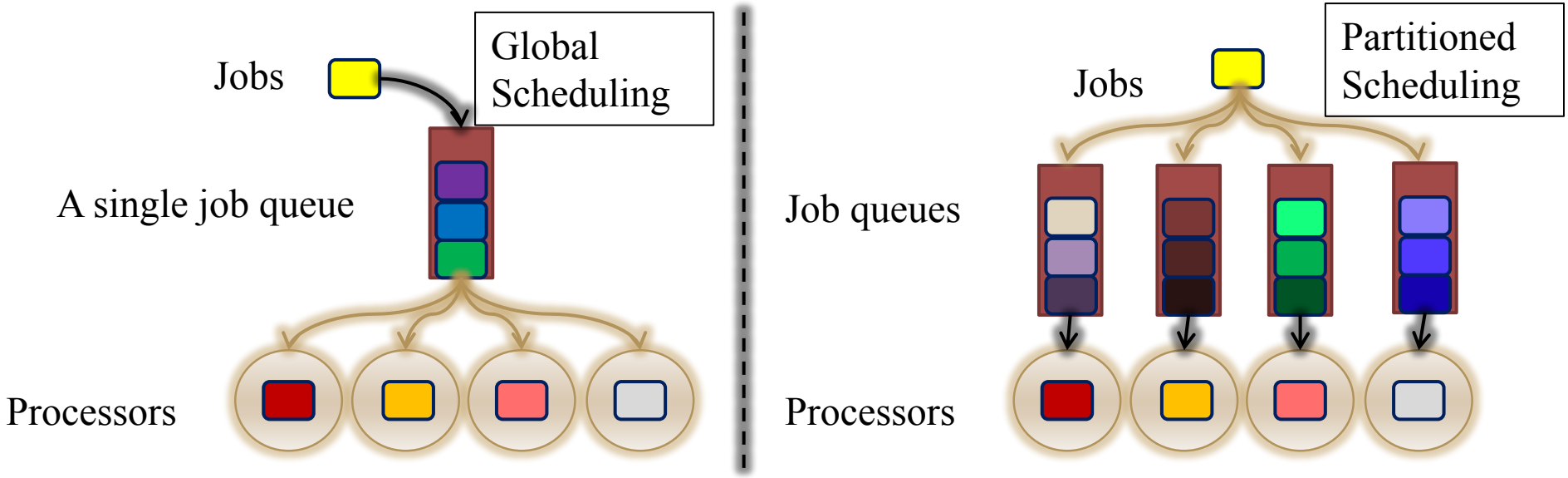


- It is free and open-source for academic
- But it is not stable
- http://www.comp.nus.edu.sg/~rpembed/chronos/

Multi-Core Scheduling

Scheduling on Multiple Cores (1/2)

- Real-Time Multi-Core Scheduling Algorithms [1]
  - Global scheduling algorithms [2]
  - Partitioned scheduling algorithms [3]



[1] Robert I. Davis and Alan Burns, "A Survey of Hard Real-Time Scheduling for Multiprocessor Systems," in *ACM Computing Surveys*, 2011.
[2] Hennadiy Leontyev and James H. Anderson, "Generalized Tardiness Bounds for Global Multiprocessor Scheduling," in *RTSS*, 2007.
[3] Sanjoy Baruah and Nathan Fisher, "The Partitioned Multiprocessor Scheduling of Sporadic Task Systems," in *RTSS*, 2005.

Scheduling on Multiple Cores (2/2)

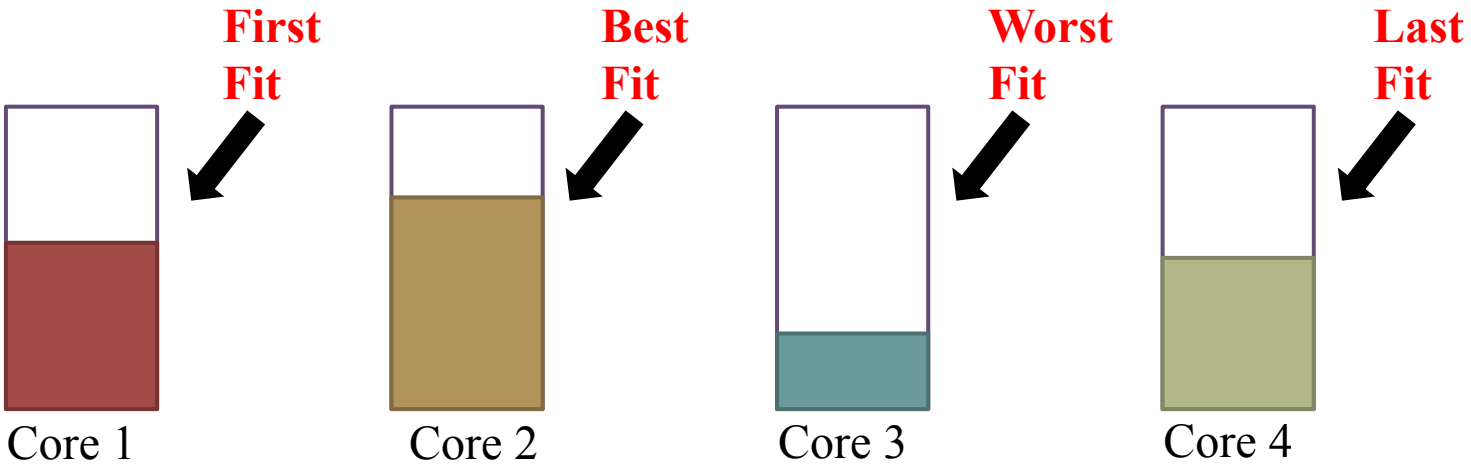
- Settings:
  - 2 cores
  - 4 tasks with execution time 5 arrive at time 0
  - 1 task with execution time 19 arrives at time 1

- Global Scheduling
  - Core 1: 
  - Core 2: 
- Partitioned Scheduling
  - Core 1: 
  - Core 2: 

Different Fitting Approaches for Partitioned Scheduling

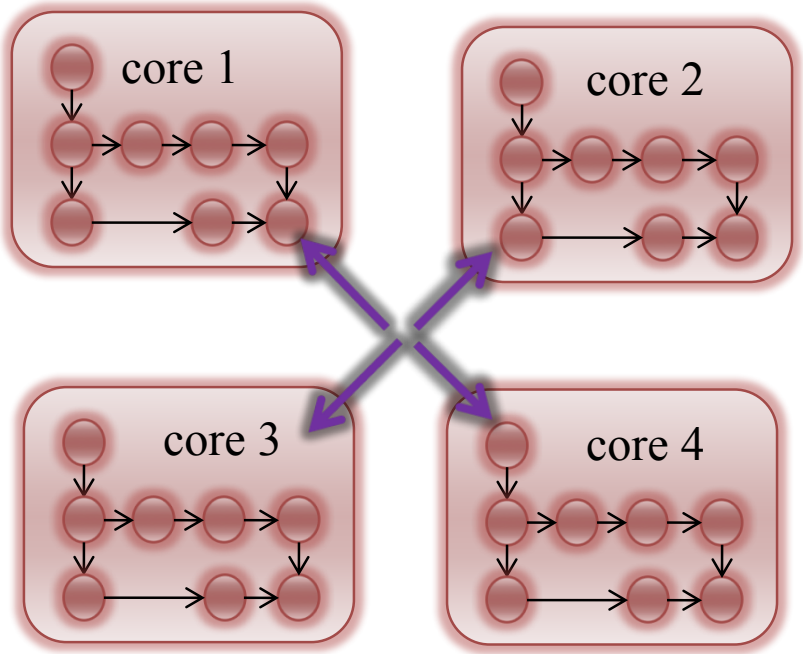
- First-Fit: choose the one with the smallest index
- Last-Fit: choose the one with the largest index
- Best-Fit: choose the one with the maximal utilization
- Worst-Fit: choose the one with the minimal utilization

Assigning a task with utilization equal to 0.1



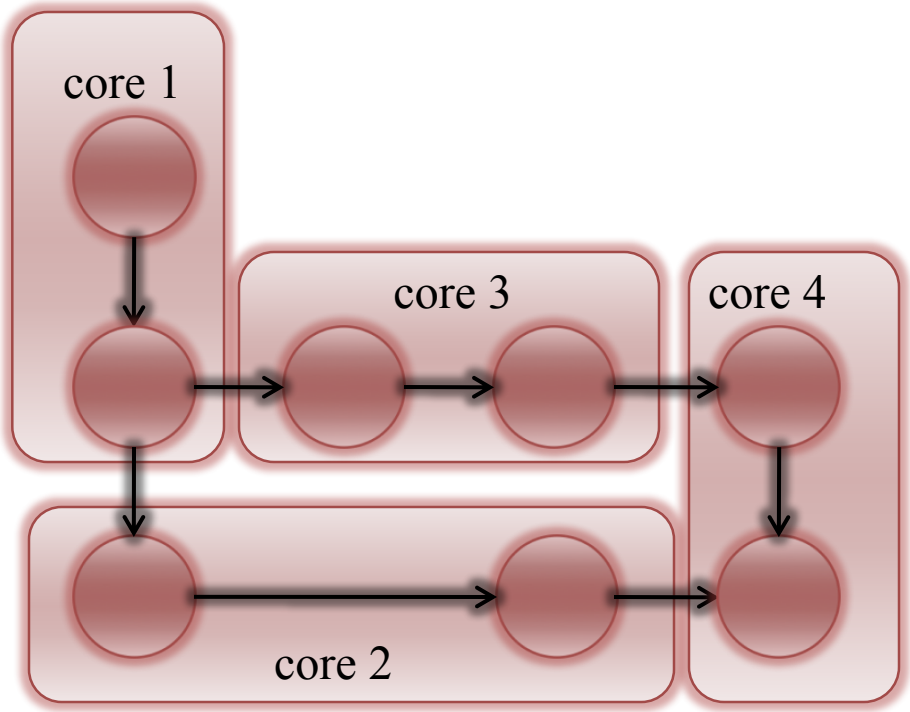
Two Approaches for Using Multiple Cores

- Data Partition



- Flexibility
- Scalability
- Load-balance

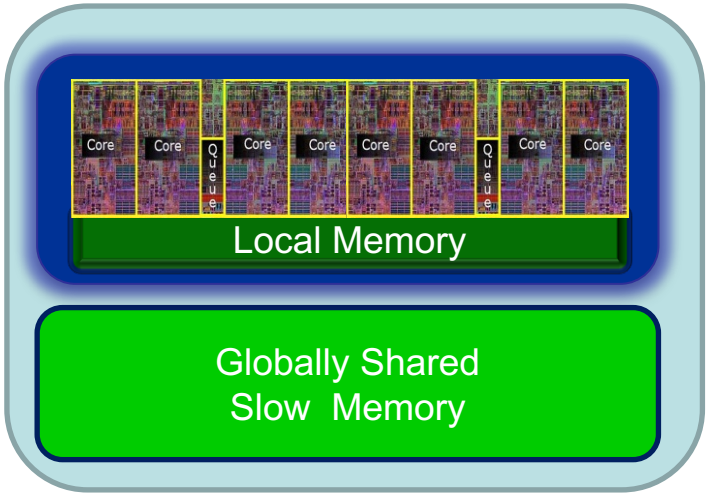
- Functional Partition



- Hardware/software co-design
- Parallelism in sequential program

Studies of Multi-Core Scheduling with Heterogeneous Memory

System Models



- Hardware Model
  - Homogeneous multiple processors
  - Two types of shared memory modules with different access latencies
  - Limited space of each memory module
- Task Model
  - An implicit-deadline sporadic task set is considered
  - Each implicit-deadline sporadic task is characterized with
    - The relative deadline
    - The minimum inter-arrival time
    - The worst case execution time
  - The worst case execution time depends on the memory allocation

Problem Definition

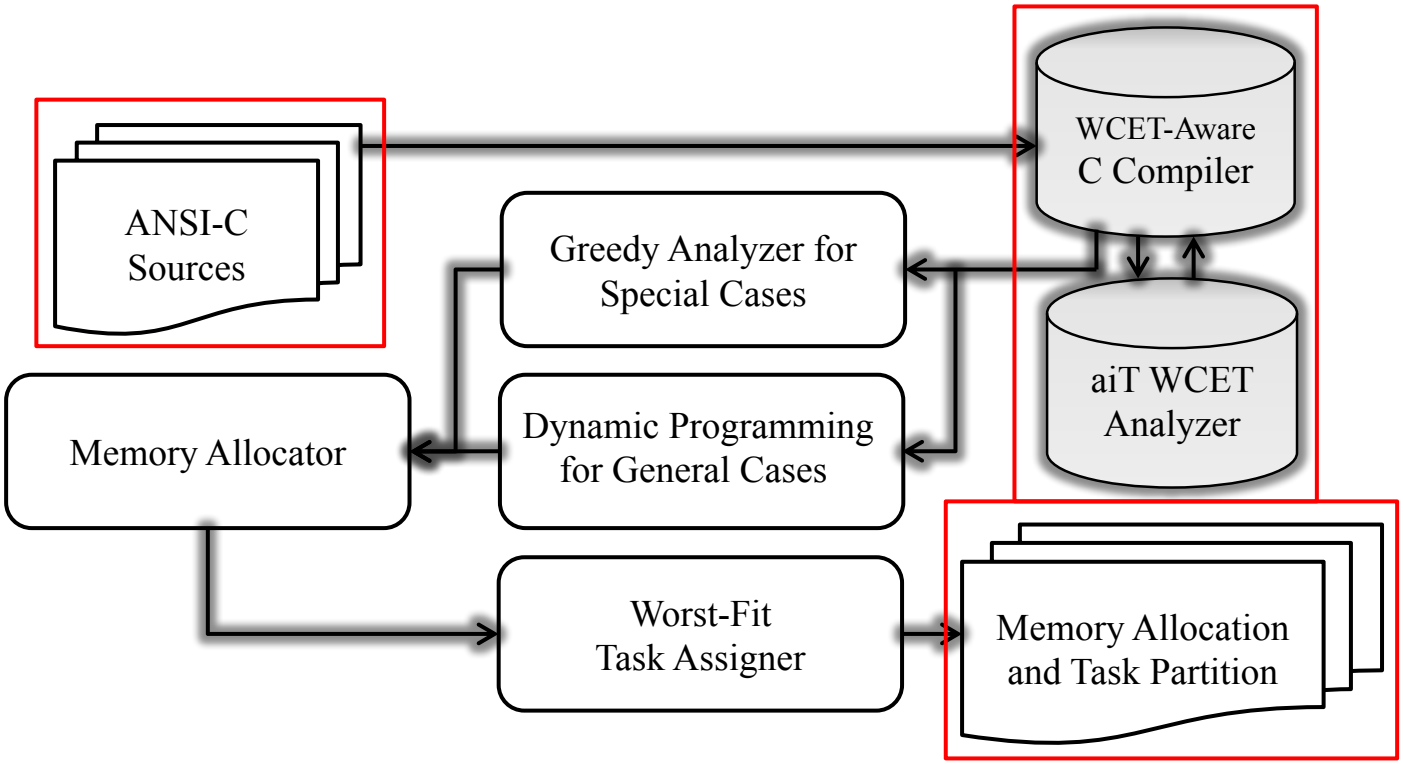
- The Goal of Our Algorithm
  - Minimize the maximum utilization of processors of a system

  ⇨ If the maximum utilization is no more than 100%, a feasible solution is derived by earliest-deadline-first scheduling scheme[1]
- The Constraints of the Problem
  - All tasks meet their deadlines
  - The required amount of blocks of each memory pool does not exceed the size of the pool

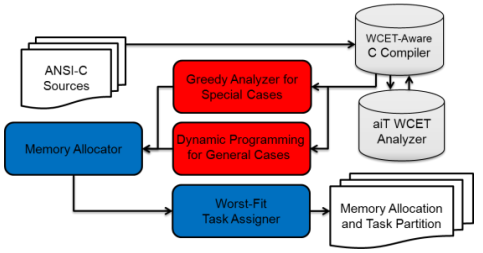
[1] C. L. Liu and James W. Layland, "Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment," in *Journal of the ACM*, 1973.

An Overview of the Proposed Solution

- Offline Profiling of the Worst Case Execution Time
- Static Memory Allocation and Task Partition



A Two-Phase Algorithm



- The First Phase: Memory Allocation
  - Produce the optimal solution of a memory allocation sub-problem
  - Derive the lower bound of the whole problem
- The Second Phase: Task Partition
  - Sort all tasks in a non-increasing order of their utilizations
  - Tasks are then sequentially assigned to the processor with the currently lowest utilization

A Lower Bound

- **Lemma 1:** if the memory allocation is already given,

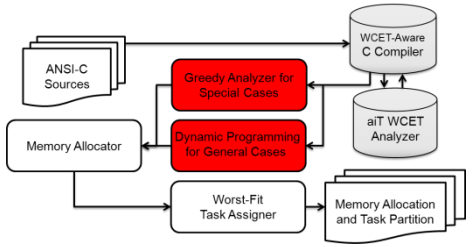
$$max\left\{max_{\tau_i \in \mathbf{T}}\{u_i\}, \frac{\sum_{\tau_i \in \mathbf{T}} u_i}{M}\right\}$$ is a lower bound

  - **T** is the task set, and M is the number of processors
  - u_i is the utilization of task τ_i with the given memory allocation

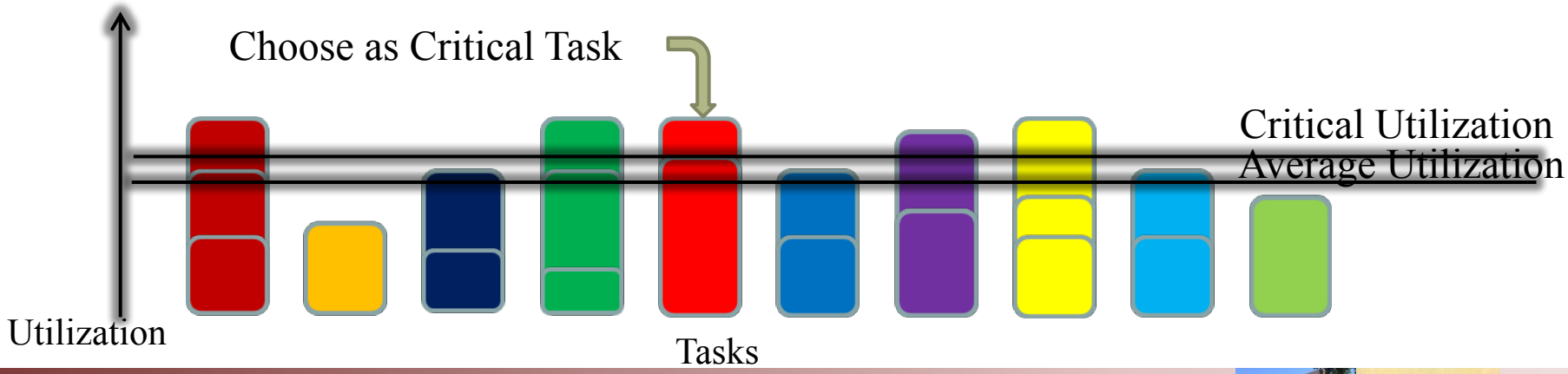
The maximum utilization amount of all tasks

The average utilization of all processors

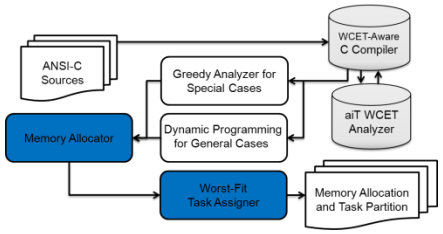
Memory Allocation—
The First Phase



1) Let task $t\tau_i$ be the task which needs the highest utilization in the optimal memory allocation result, and it consumes ℓ blocks of the fast memory pool
2) Allocate exactly ℓ blocks of the fast memory for τt_i
3) Reduce the utilization of other tasks to make sure that $t\tau_i$ has the highest utilization
4) Reduce the average utilization as much as possible
5) Iteratively try all the possible combinations of τt_i and ℓ



Task Partition—
The Second Phase

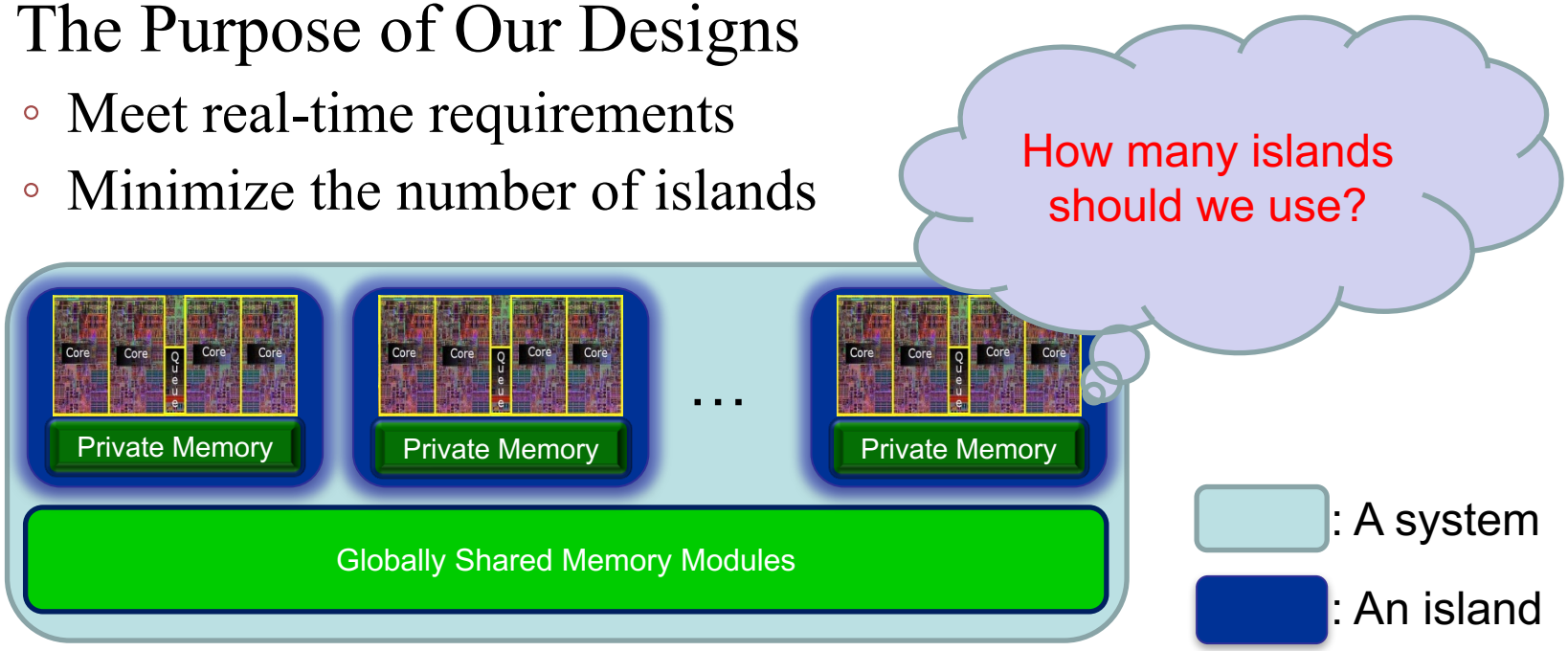


1) Based on the result of the proposed memory allocation algorithm, sort all tasks in a non-increasing order of their utilization
2) Sequentially assign tasks to the processor with the currently lowest utilization

- It takes only a polynomial time complexity
- It has a tight $(2 - \frac{2}{M+1})$-approximation bound for the minimization problem, where M is the number of processors

System Model

- An Island-Based Multi-Core Platform
  - A global memory pool and multiple islands
  - A policy to turn on/off islands to manage resources
- The Purpose of Our Designs
  - Meet real-time requirements
  - Minimize the number of islands

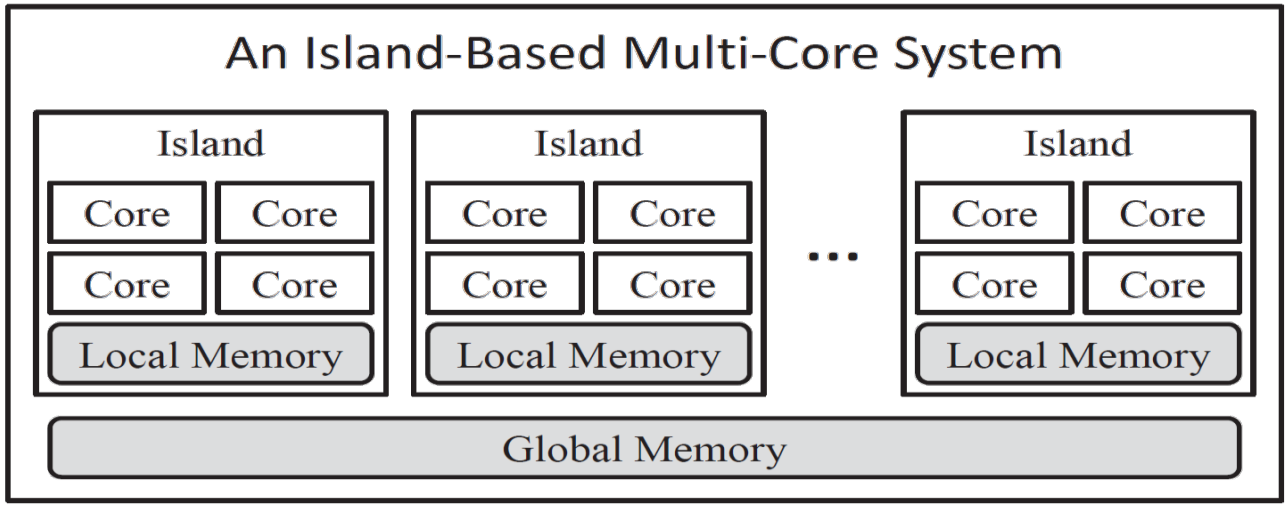


Problem Definition– Real-Time Tasks

- Goal:
  - Minimize the number of required islands
- Constraints:
  - All implicit-deadline sporadic tasks meet their deadlines
  - No memory space limitation is violated
- Task Model– Implicit-Deadline Sporadic Tasks:
  - A relative deadline
  - The minimum inter-arrival time
  - The worst case execution time

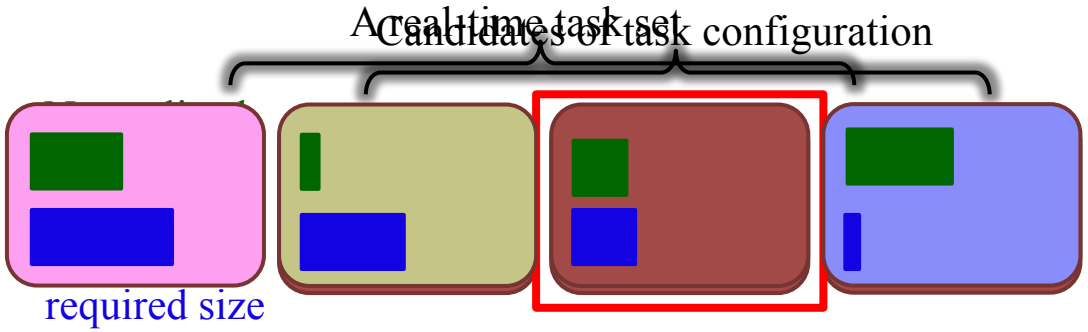
Problem Definition– Hardware Platforms

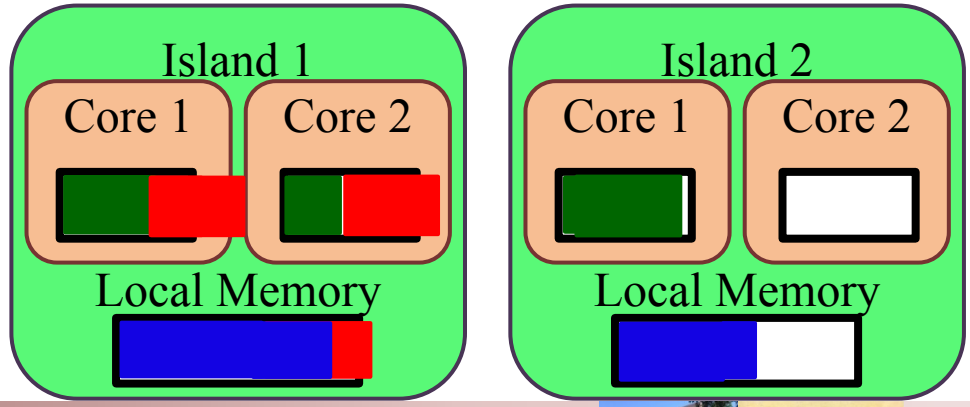
- Hardware Model– Island-Based Multi-Core Platforms:
  - Cores in an island share a local memory pool
  - An island consists of multiple homogeneous cores
  - A system consists of multiple islands
  - A system consists of a large global memory pool



Proposed Algorithms

1. Minimize the value of $\frac{U_i^j}{M} + \frac{j}{B_L}$ for each task
2. Sort all tasks in a non-increasing order by the required number of the local memory blocks
3. Partition all tasks to islands by the first fit strategy
4. Assign tasks onto cores by the first fit strategy
5. Allocate a new island if there is no feasible assignment for a task





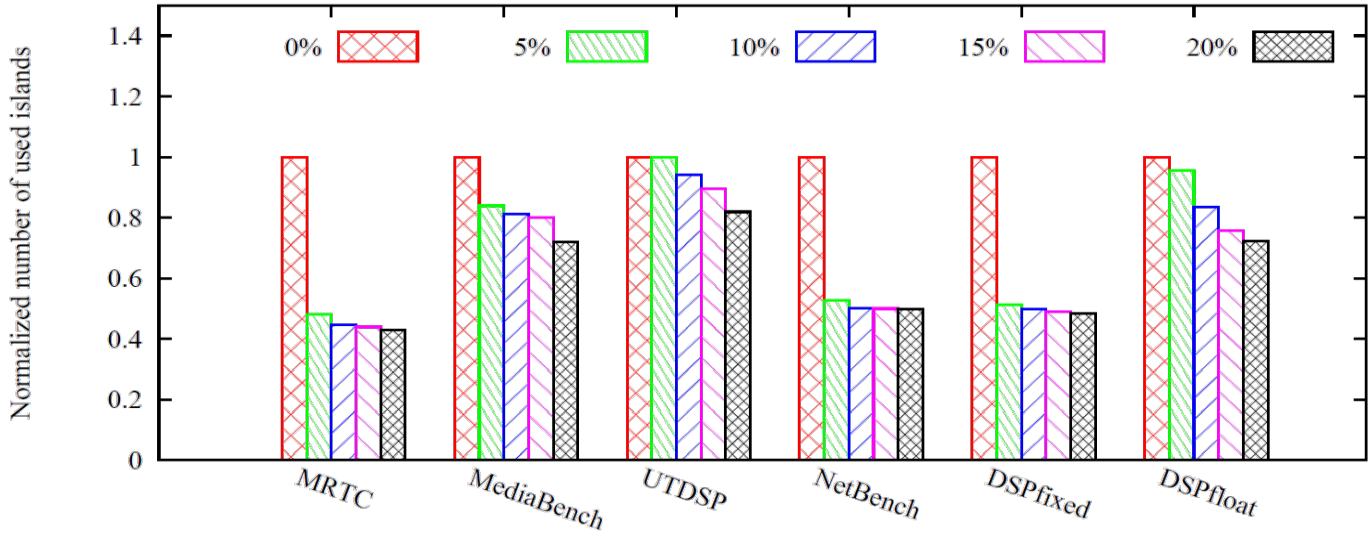
54

Analysis of the Algorithm

- ***Theorem 3***: the properties of the algorithm
  - The time complexity is $O(|\mathbf{T}|^2 + \gamma)$, where $|\mathbf{T}|$ is the number of task, and γ is the number of the candidates of memory allocation
  - The derived result (number of the required islands) is bound by $4OPT + 2$, where OPT is the result of the optimal solution
- The value of the proposed algorithm
  - Provide the lower bound for an IBRT problem instance
  - Provide a bounded solution for island-based multi-core system synthesis

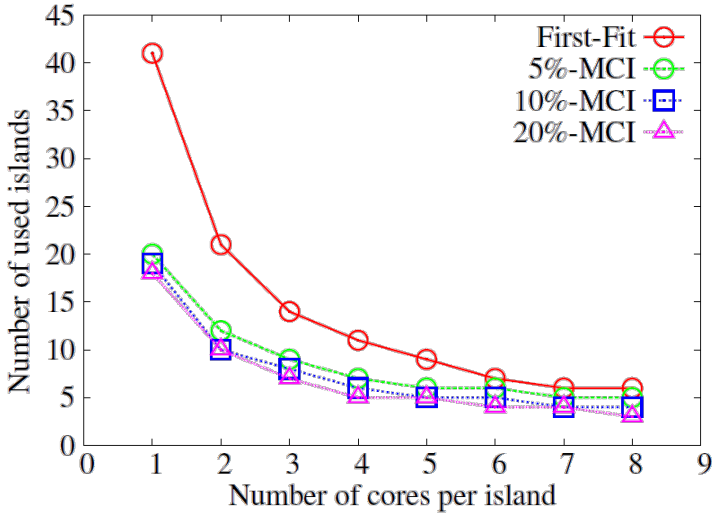
Performance Evaluation (1/2)

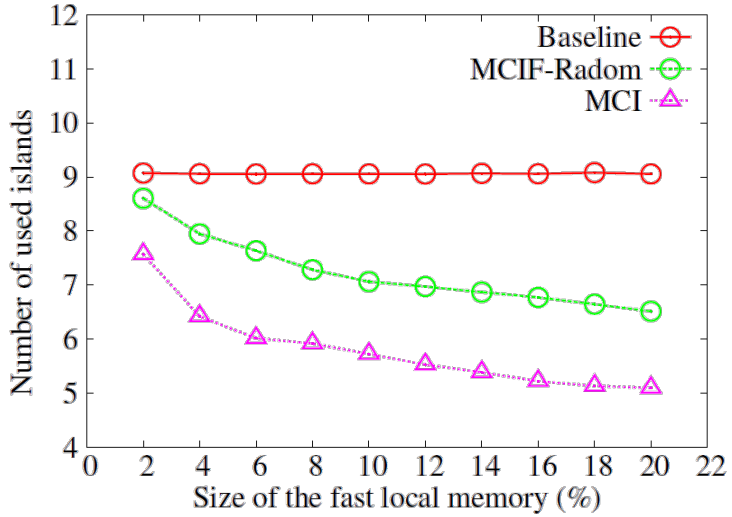
- 82 real-life benchmarks from MRTC, MediaBench, UPDSP, NetBench, and DSPstone
- The worst-case execution time of each task is generated by aiT which is based on Infineon TriCore TC1797
- The number of cores in an island is 4



Performance Evaluation (2/2)

- Include the 82 benchmarks for the two experiments
- Vary the number of cores per island for the left experimental results
- Vary the size of the local memory for the right experimental results

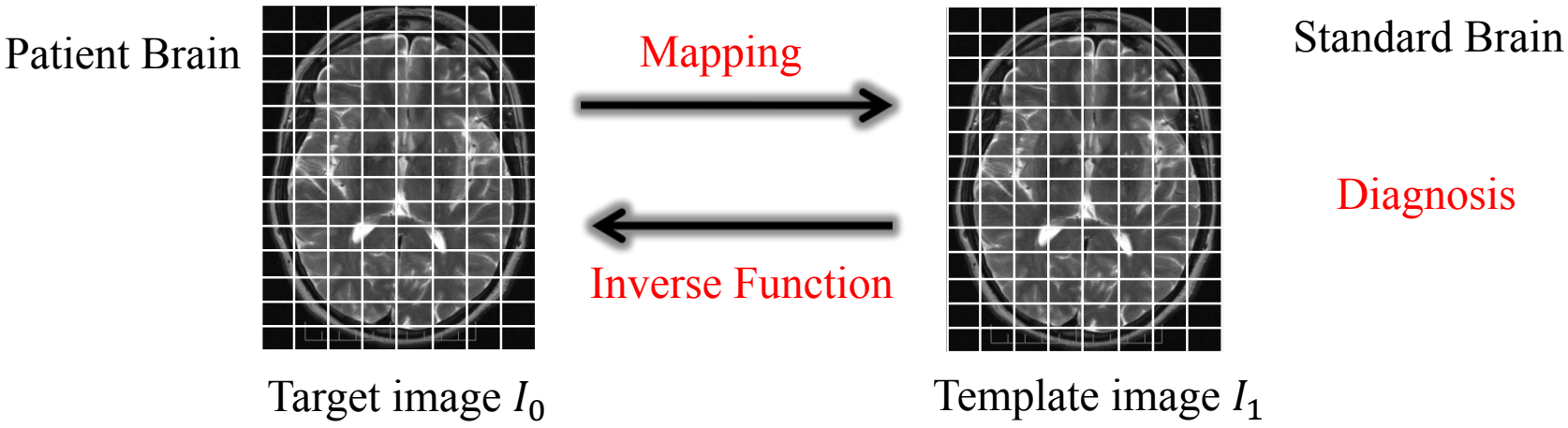




Studies of Heterogeneous Computing Resources

Image Registration

- LDDMM-DSI conducts image registration while preserving the topology conservation and invertibility
- However, the precision of the outcome is at the expense of the execution time
- Why we need image registration?

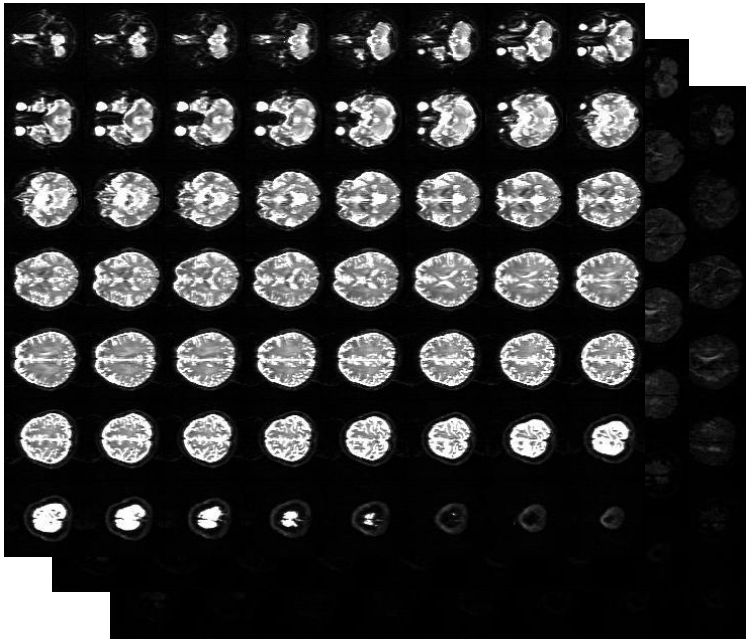


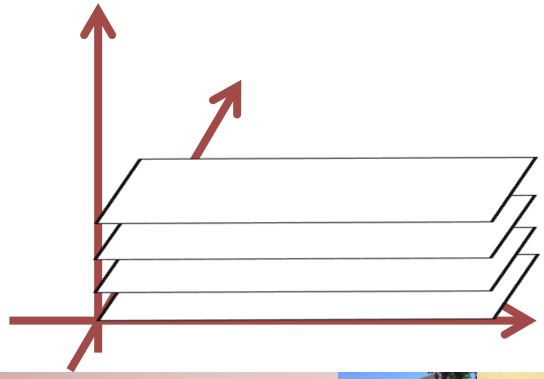
LDDMM–DSI

- LDDMM-DSI
  - A large deformation diffeomorphic metric mapping solution for diffusion spectrum imaging datasets
- Motivation
  - Medical Image Center
    - Huge amount of medical images are received for processing
    - How to exploit the throughput becomes important
  - Instant checking of many different possible diseases
    - Different weighted MRI images target different soft tissues
    - Thus, different registration processes will be required to conduct thorough checking

Input/Output Data

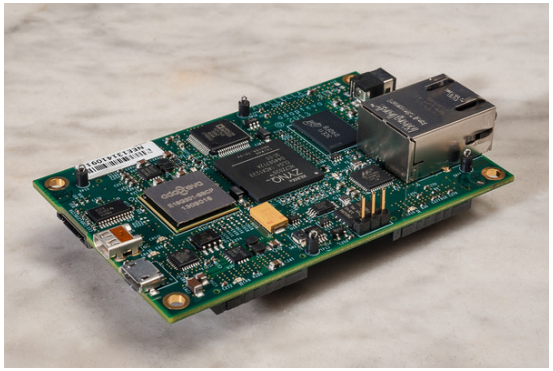
- The input data contain both i-space(3D) and q-space(3D)
- The output data contain mainly the velocity files, which is around 2GB in total
- The intermediate data are larger than 30GB





Trends of FPGA

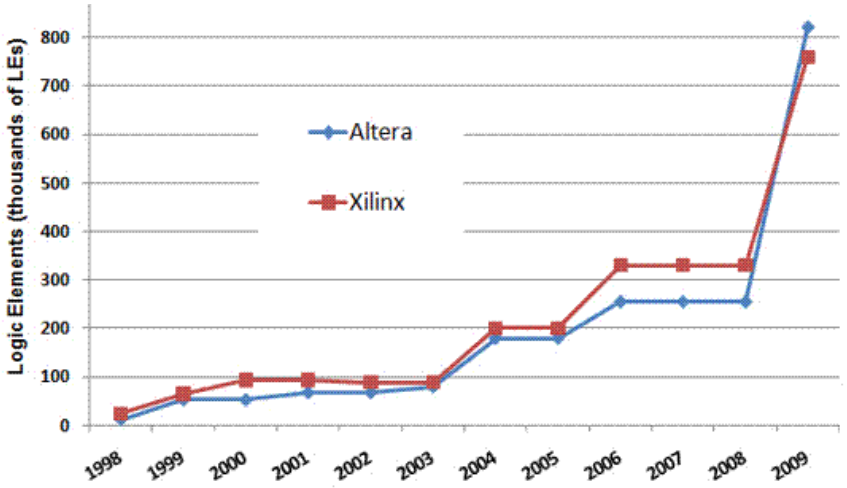
Price dropping



Parallela board
(Xillinx FPGA)

99.0 USD

Logic Element count growing (exponentially!)

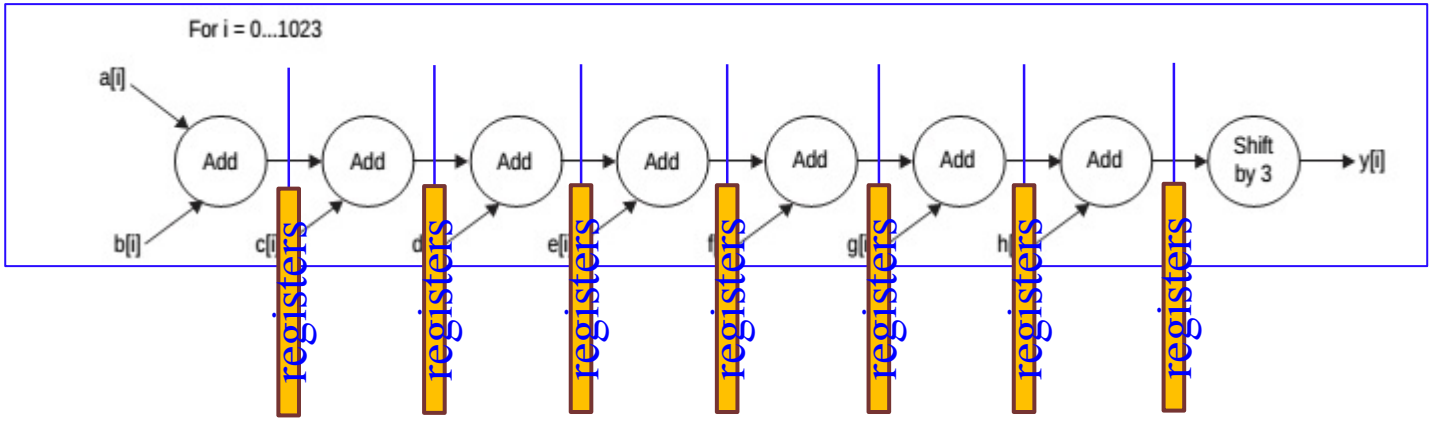


Source: http://www.xilinx.com/partners/90nm/ http://www.soccentral.com/results.asp?CatID=488&EntryID=30730

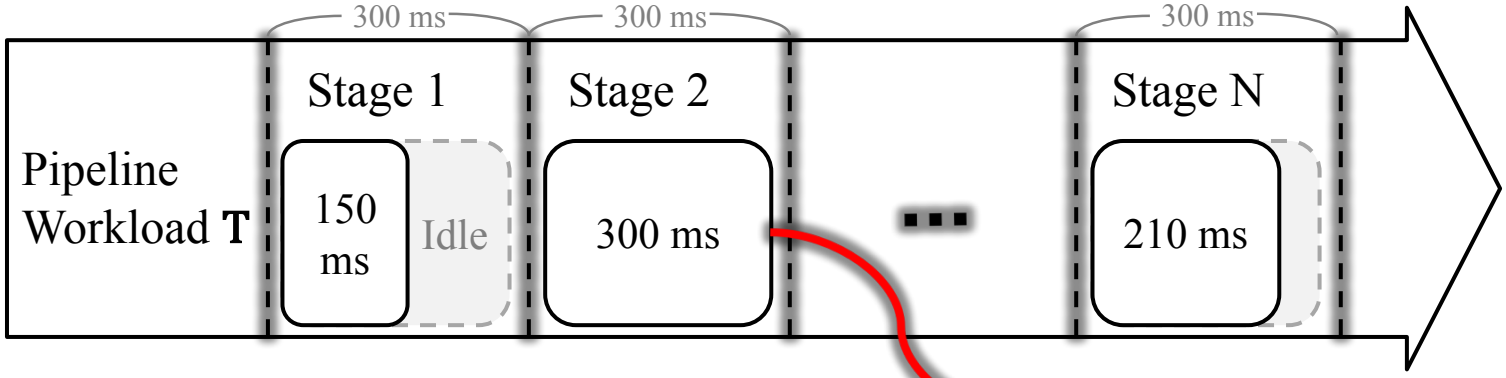
Pipeline Designs of FPGA

- Acceleration Techniques on FPGA
  - Customized Datapath
  - Pipelined Execution

```
for(i = 0; i < 1024; i++)
{
   y[i] = (a[i] + b[i] + c[i] + d[i] + e[i]+ f[i] + g[i] + h[i]) >> 3;
}
```



Challenges

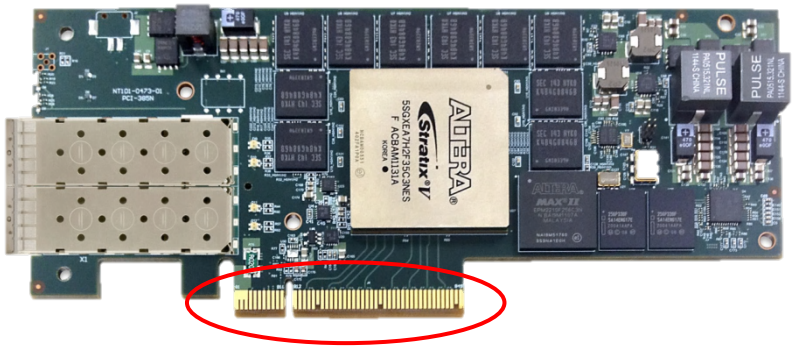


- Since throughput = $\frac{1}{\text{longest stage time}}$

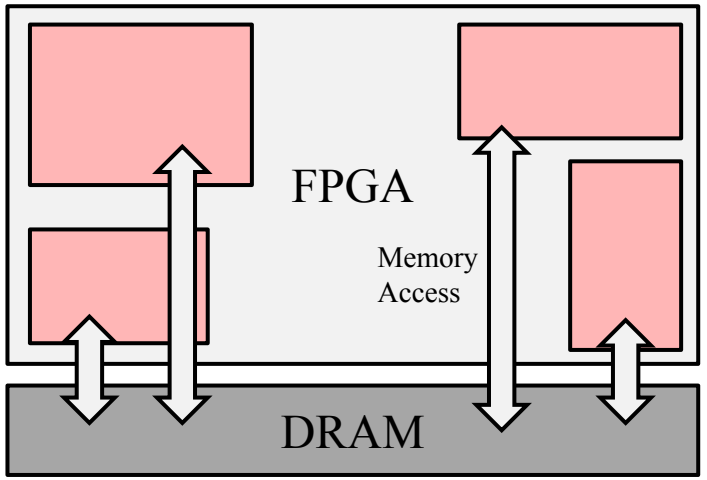
- To achieve optimal performance:
  - Minimize idle time
  - Trade **area** and **bandwidth** for performance
    - Area and bandwidth are limited resource!

FPGA Device Model

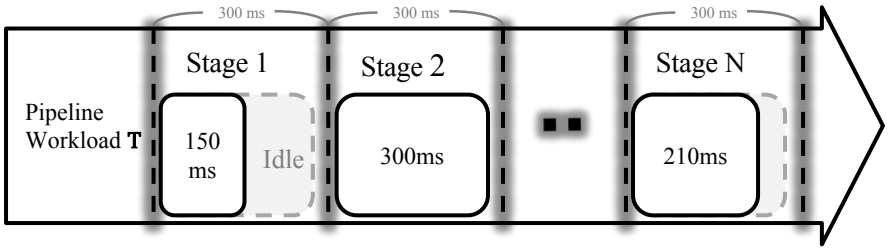
- Example: Nallatech PCIE 385n (Altera Stratix V A7 FPGA)
  - Logic element count: 622000
  - Memory bandwidth: 25 GB/s



- Model:
  - A: total area (gate count)
  - B: total memory bandwidth



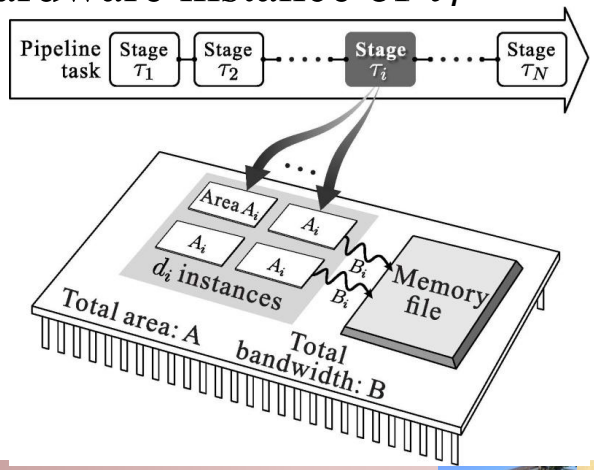
Task Model



- A **pipeline** workload **T** has N stages of execution
  - The i-th stage τ_i has a degree D_i of ***data parallelism***
- When a **hardware instance** of τ_i is programmed on FPGA
  - Consumes FPGA ***area***: A_i
  - Requires ***memory bandwidth***: B_i
  - Requires time T_i to execute a single work-item
- Let d_i be the **number of** programmed hardware instance of τ_i
  - Required area: $A_i d_i$
  - Required bandwidth: $B_i d_i$
  - Execution time: $T_i \left\lceil \frac{D_i}{d_i} \right\rceil$

Time to process a batch

Number of batches



Problem Definition

- METM (**M**aximum **E**xecution **T**ime **M**inimization problem)
- Problem definition:

Minimize

$$\max_{\forall \tau_i \in \mathbf{T}} \left\{ \mathrm{T_i} \left\lceil \frac{D_i}{d_i} \right\rceil \right\}$$

Stage execution time

Pipeline stage time

subject to

$$\sum_{\forall \tau_i \in \mathbf{T}} A_i \cdot d_i \leq A$$

Area constraint

$$\sum_{\forall \tau_i \in \mathbf{T}} B_i \cdot d_i \leq B$$

Bandwidth constraint

$$1 \leq d_i \leq D_i, \forall \tau_i \in \mathbf{T}$$

Dynamic Programming Solution

- DP-based algorithm: DP-METM (Maximum Execution Time Minimization)

min time of first x-1 stages

exec time of x-th stage

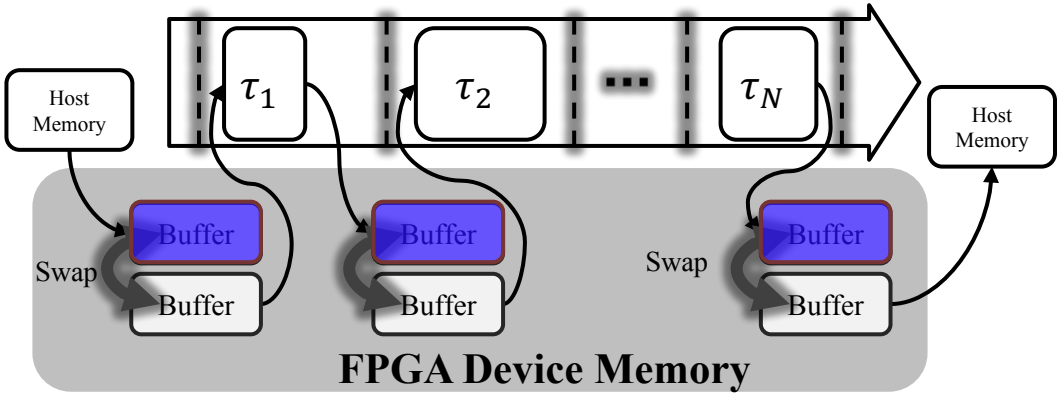
$$v(x,a,b) = \begin{cases} \min\limits_{1 \le d_x \le D_x} \left\{ \max\left\{ v(x-1, a', b'),\ T_x\left\lceil \frac{D_x}{d_x} \right\rceil \right\} \right\}, & \text{if } \begin{cases} 0 \le a \le A \\ 0 \le b \le B \end{cases} \\ \infty, & \text{otherwise} \end{cases}$$

Where $a' = a - A_x \cdot d_x$, $b' = b - B_x \cdot d_x$ and $x \ge 1$

- Algorithm DP-METM is optimal
- Complexity of DP-METM is: $O(|\mathbf{T}| \cdot A^2 \cdot B)$

Implementation Remarks

- Input parameter measurement
  - A_i, B_i can be obtain from the compiler output
  - T_i need to be measured manually
- Runtime library support
  - Dispatch stage workload
  - Exchange data between stages



- Example platform: Nallatech PCIE 385n [1] FPGA card
  - Using OpenCL toolchain

[1] N. Coporation, "Nallatech 385 Product Brief," Feb 2014.

Conclusion

- Summary
  - Energy-efficient multimedia platforms
  - Partitioned scheduling algorithms for multi-core systems with heterogeneous memory devices
  - Fast booting techniques with nonvolatile memory
- Insights
  - The design of the memory architecture of multi-core systems is with increasing importance
  - CPU is not the only resource which should be considered in multi-core real-time scheduling