Using Performance Counters for Runtime Temperature Sensing in High-Performance Processors

Kyeong-Jae Lee and Kevin Skadron

LAVA Lab
Dept. of Computer Science
University of Virginia
Charlottesville, VA

Outline

- **Motivation**
- **Runtime Thermal Modeling**
- **Case Studies**
- **Future Work**

Motivation

- Thermal Management Techniques
  - Operate at processor architecture level
  - Require ability to measure temperature
- Thermal Sensors
  - Analog CMOS circuits
  - Costly to implement
  - Difficult to calibrate
  - May exacerbate thermal problem

AMD Athlon (Source: Toms Hardware)

Motivation (cont.)

- Placement of sensors
  - Only small number available on CPU
  - Thermal security risks
- Other Uses
  - Temperature-aware scheduling
  - Thermal profiling
  - Etc
- Example: Pentium 4

Outline

- Motivation
- Runtime Thermal Modeling
- Case Studies
- Future Work

Pentium 4 Processor

- Northwood core (130 nm)
- Performance monitoring
  - 48 configurable micro-architectural events
  - 18 performance counters
- One software-visible thermal sensor
- Supports hyper-threading

Pentium 4

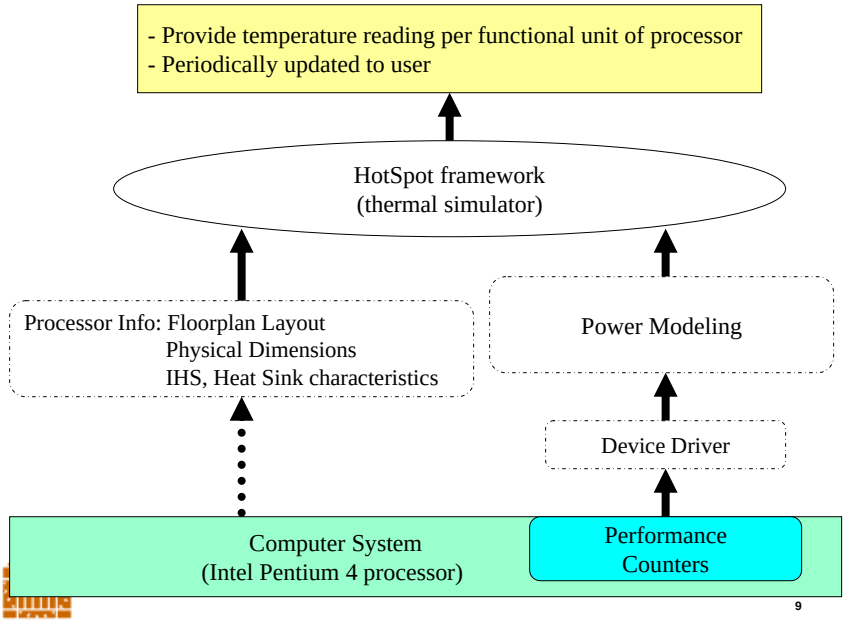
Intel Pentium 4 Northwood photo (Source: Intel website)

Runtime Thermal Modeling

- **Floorplan-level detail**
  - **Provides one temperature reading for every functional sub-unit**
- **Performance Counters**
  - **Available in most processors**
  - **Infer processor activity based on real hardware**
- **Use at runtime under real workload**

8

Methodology



Methodology

- **Extend *HotSpot***
  - **Thermal simulator developed by LAVA lab**
  - **Computes temperature from localized power data**
  - **Requires floorplan layout**
- **Power modeling**
  - **Use performance counters to derive power value per block (Isci and Martonosi, MICRO 2003)**

$$Power = (MaximumPower) \times (Architectural\ Scaling) \times (Access\ Rate) + (Idle\ Power)$$

Implementation Details

- Default sampling interval
  - Counter configuration: 5 ms
  - HotSpot temperature calculation: 20 ms
- Overhead
  - Thermal overhead of 1 ~ 3 ºC (compared to 2 ~ 10 ºC for other benchmarks)
  - Execution time of SPEC2000 benchmarks
    - Integer benchmarks: 20~35% increase
    - Floating-point benchmarks: 10~50% increase
- Proof-of-concept

Limitations

- Runge-Khutta-Fehlberg method
  - Requires several iterations
  - High overhead for compute-intensive applications
- Need for counter rotations may miss events
  - Some activities only sampled 50 % of the time; FP only 25% of the time
  - Sampling period is 5 ms
  - Affecting temperature requires sustained activity
- Accuracy depends on many parameters
  - Performance metrics
  - Power factors
  - Processor package information

Outline

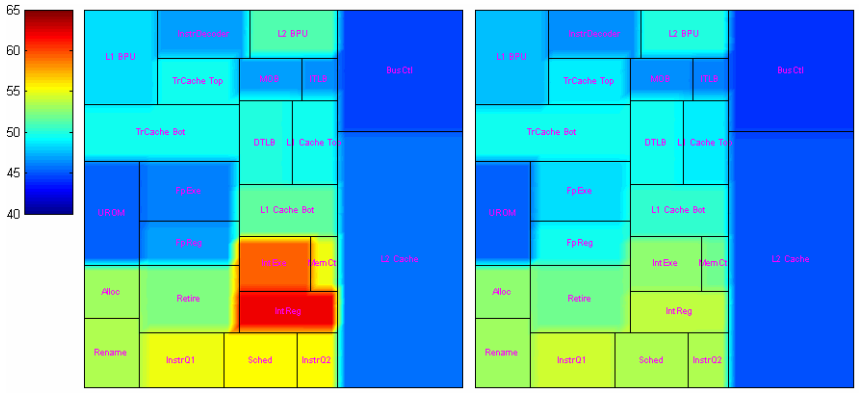
- Motivation
- Runtime Thermal Modeling
- Case Studies
- Future Work

Thermal Stress Patterns

- Spatial Variations
  - Integer vs. Floating-point
  - Identify thermal gradient bounds
- Temporal Variations
  - Movement of hot spot

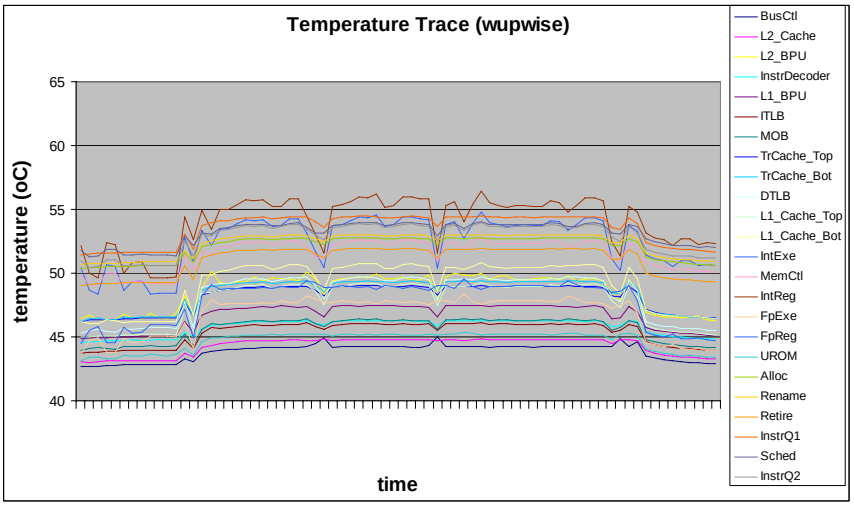
Thermal Plots

- **Integer vs. FP**

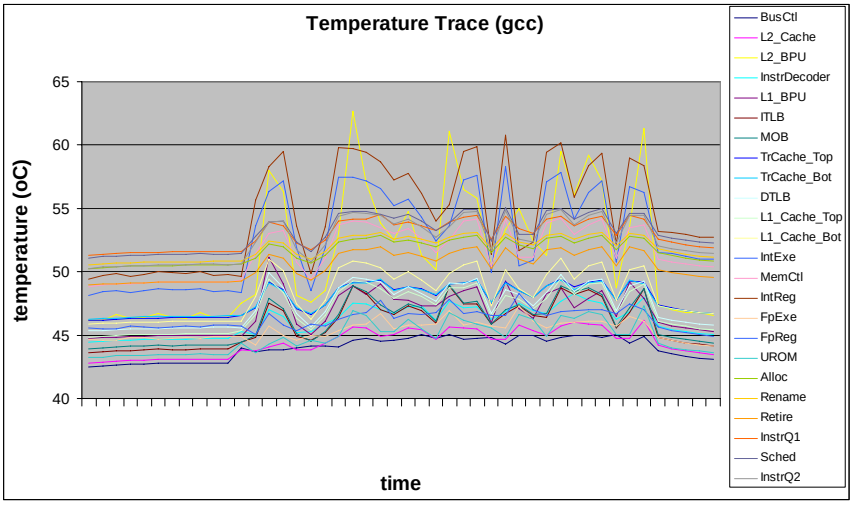


SPEC gzip (integer) *SPEC wupwise (FP)*

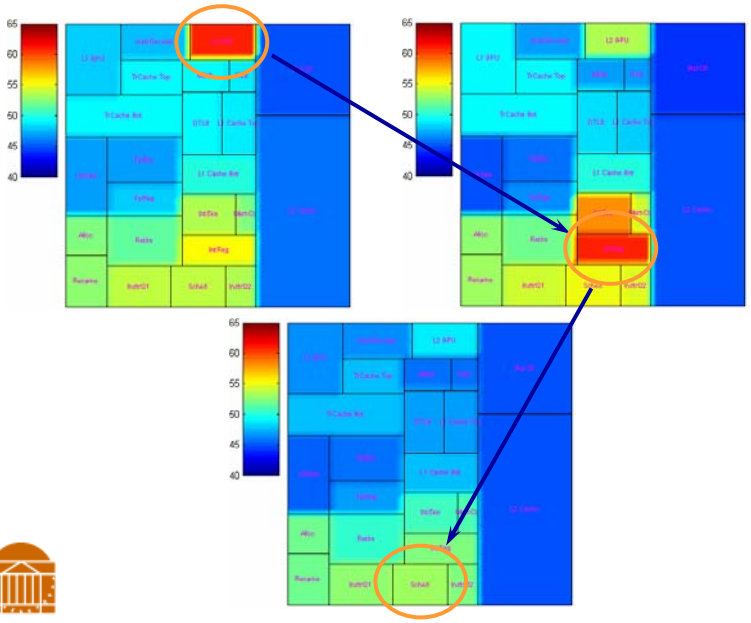
FP Benchmarks



Integer Benchmarks



Hot Spot Movement (gcc)



Outline

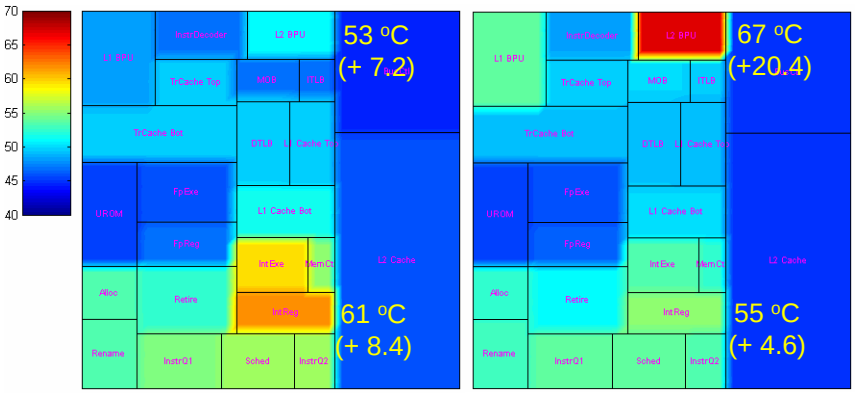
- Motivation
- Runtime Thermal Modeling
- Case Studies
- Future Work

Hardware Design Guides

- Custom packaging for integer / FP applications
  - E.g., super computer vs. data center
- Sensor placement
  - Protection against thermal viruses
- Thermal design margin
  - Study localized heating effects
  - Thermal viruses
- Hybrid SW-HW solution

More About Thermal Viruses

- **Selective heating of units**



SPEC gzip *BPU stressmark*

Future Work

- **Improve performance and accuracy of model**
  - **Faster numerical methods**
  - **On-chip sensor validation**
- **Study thermal security attacks**
- **Explore sensor-fusion algorithms**
  - **Combine thermal sensors and software model**
  - **Minimize computation**
  - **Take advantage of existing sensors**

Questions

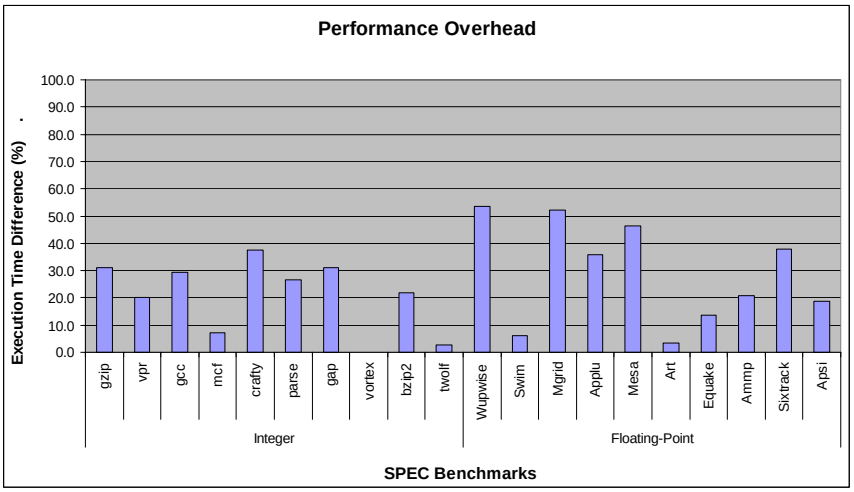
- **Thank you!**

Backup Slides

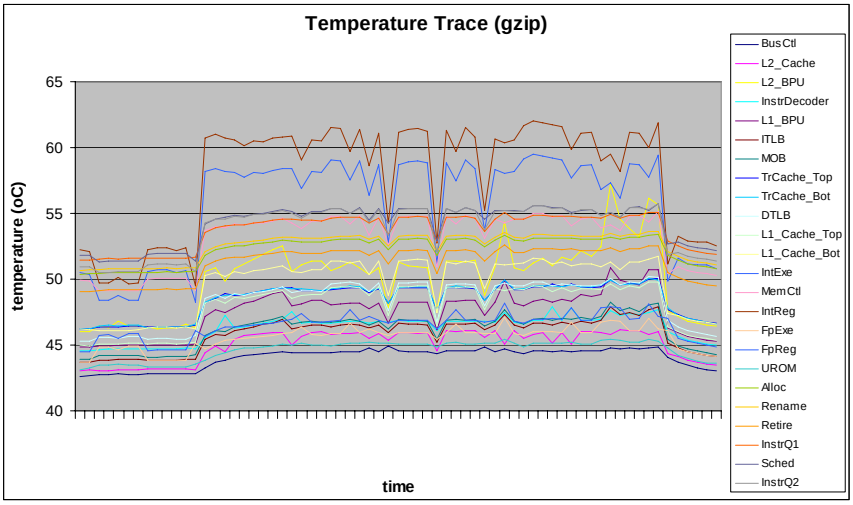
HotSpot Configuration

HotSpot variable	Value	Description (Unit)
t_chip	0.74	chip thickness (mm)
c_convec	131.84	convection capacitance (J/K)
r_convec	0.084	convection resistance (K/W)
s_sink	76	heat sink side (mm)
t_sink	12	heat sink thickness (mm)
s_spreader	31	heat spreader side (mm)
t_spreader	1.5	heat spreader thickness (mm)
t_interface	0.05	interface material thickness (mm)
ambient	40+273.15	ambient temperature (K) (inside box)
roughness	0.8	roughness factor of package surface (0.0~1.0)
RHO_INT	0.315	thermal resistivity of interface material (mK/W)
SPEC_HEAT_INT	3.96E+06	specific heat of interface material (J/m^3K)

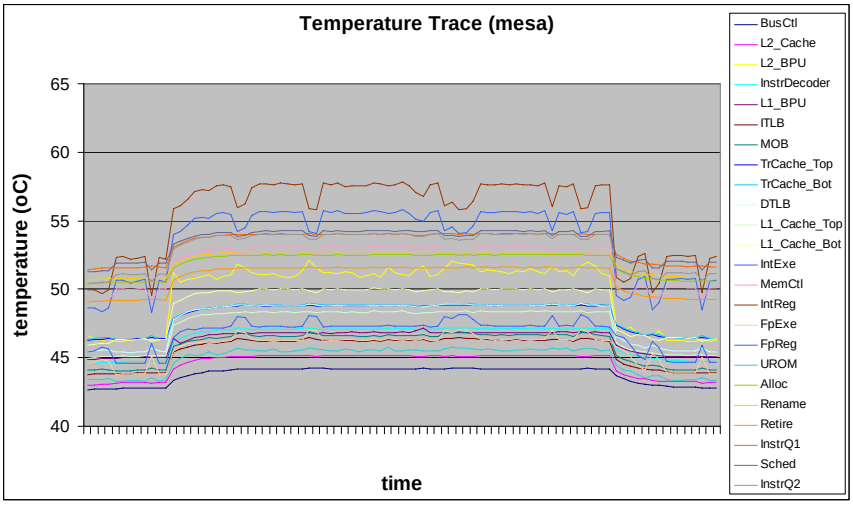
Performance Overhead



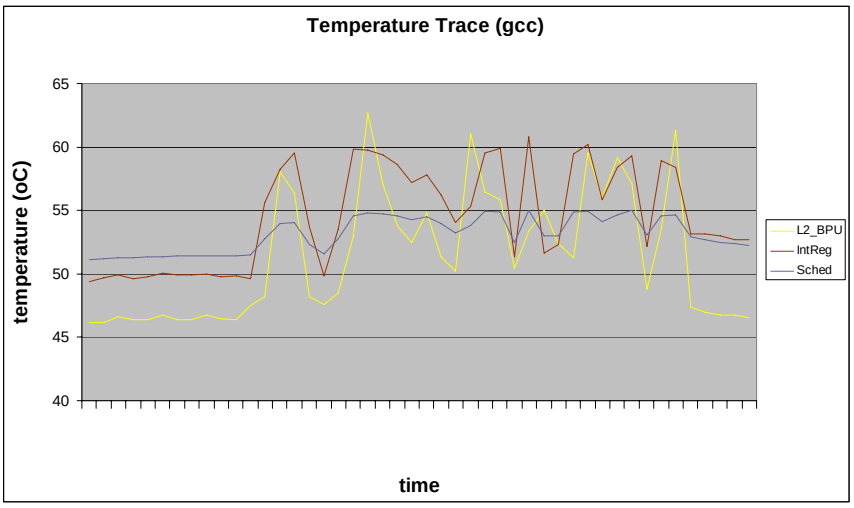
Spatial Variations



Spatial Variations

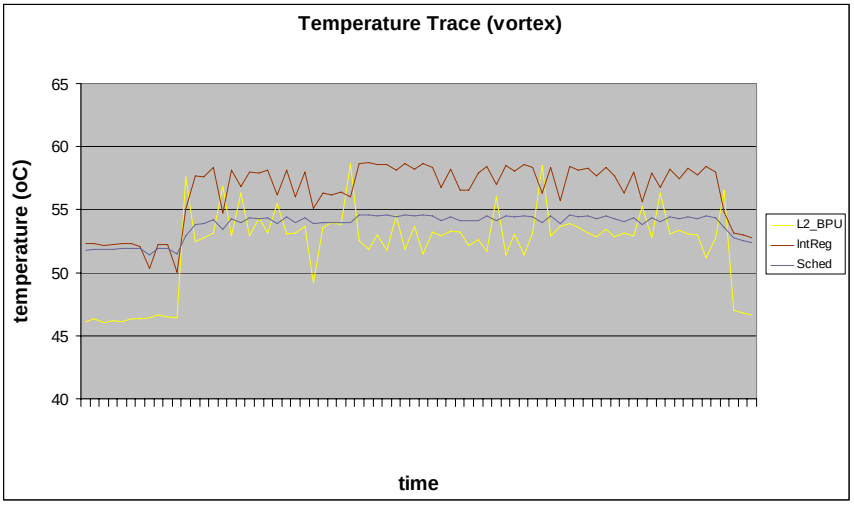


Temporal Variations



29

Temporal Variations



30