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# An Energy Characterization Framework for Software-Based Embedded Systems

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# Outline

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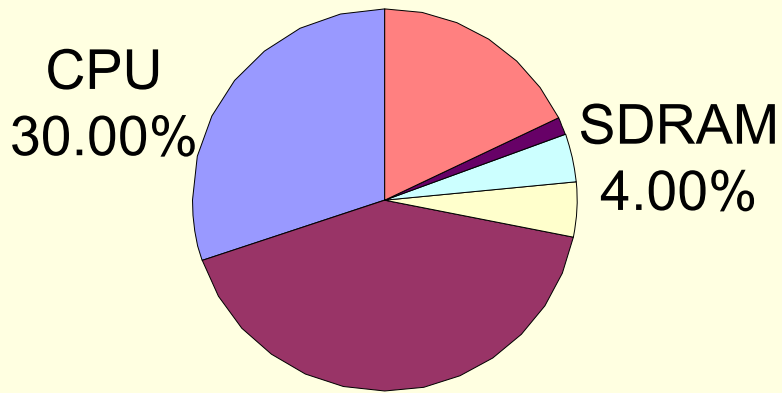
- Introduction
- Energy characterization framework
- Training bench generation
- Experimental results
- Summary

# Back Ground (1/2)

## ***Power consumption at a processor on embedded system has a big portion***

### Power Distribution in a PDA class sample device

Cliff Brake, Accelent Systems, Inc. (May, 2003)

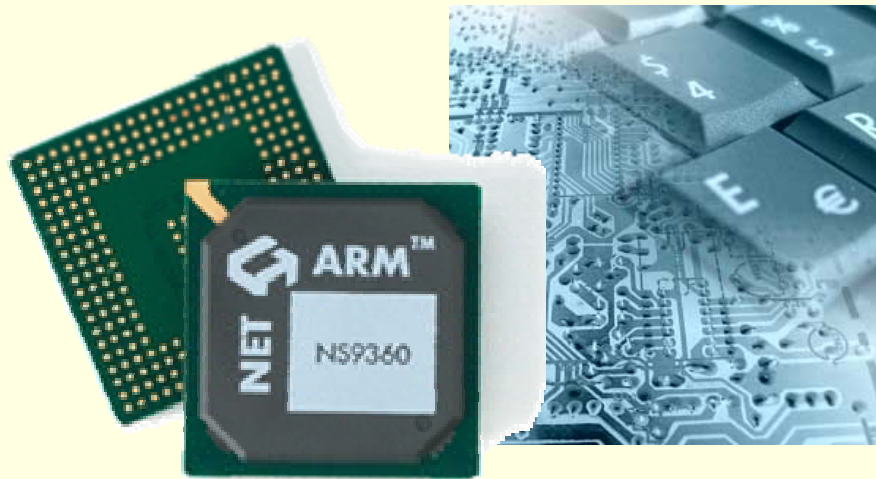


[www.princeton.edu/~wolf/](http://www.princeton.edu/~wolf/)

## Back Ground (2/2)

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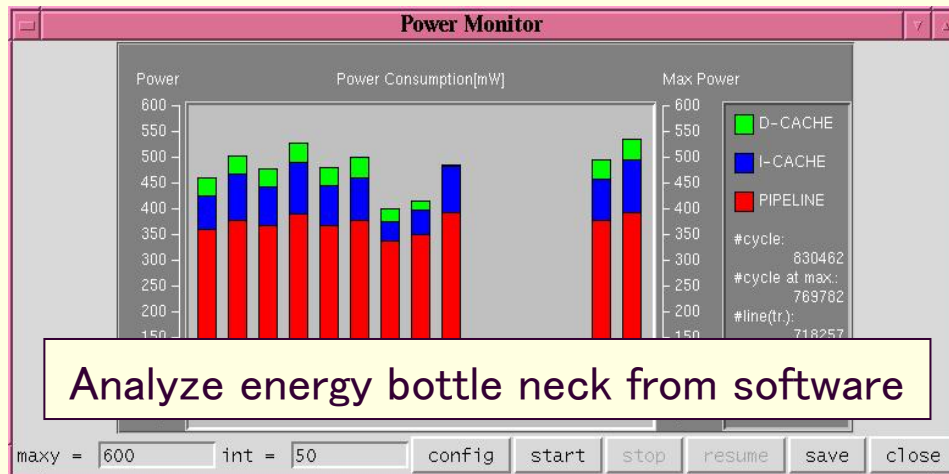
***Power consumption at a processor depends on the software being executed***



***SW designer should think power dissipation by SW that he is developing***

# Energy Analysis Tool

***We propose a characterization technique to find a good energy model for a processor***



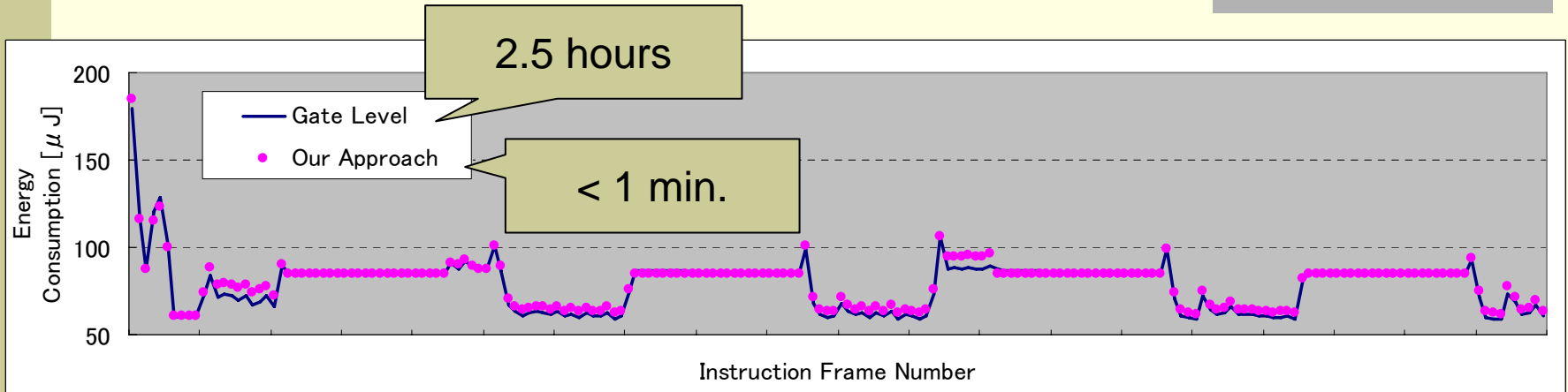
The Source Window window displays assembly code for a program named "icmst". The code is shown in hexadecimal and assembly format. A text box at the bottom of the window contains the text "Use GDB as ISS".

```
0x290440 <icmst>: ld24 r1,0x2a2430 <data0>
0x290444 <icmst+4>: ld24 r2,0x2a2434 <data5>
0x290448 <icmst+8>: ld24 r3,0x2a2438 <dataa>
0x29044c <icmst+12>: ld24 r4,0x2a243c <dataf>
0x290450 <icmst+16>: ld r1,@r1 -> ld r2,@r2
0x290454 <icmst+20>: ld r3,@r3 -> ld r4,@r4
0x290458 <icmst+24>: ldi r8,#256
0x29045c <icmst+28>: addi r1,#0 || nop
0x290460 <icmst+32>: ld24 r5,0x2a2440 <ldst>
0x290464 <icmst+36>: st r1,@r5 -> bra 0x290470 <icmst+48>
0x290468 <icmst+40>: addi r1,#0 -> addi r1,#0
0x29046c <icmst+44>: addi r1,#0 -> addi r1,#0
0x290470 <icmst+48>: st r2,@(16,r5)
0x290474 <icmst+52>: bra 0x290480 <icmst+64> || nop
0x290478 <icmst+56>: addi r1,#0 -> addi r1,#0
0x29047c <icmst+60>: addi r1,#0 -> addi r1,#0
0x290480 <icmst+64>: > || nop
0x290484 <icmst+68>: #0
0x290488 <icmst+72>: #0
0x290492 <icmst+76>: #0
0x290496 <icmst+80>: > || nop
0x29049c <icmst+84>: addi r1,#0 -> addi r1,#0
0x2904a0 <icmst+88>: st r1,@(64,r5)
Program stopped at 290440 0x290440
```

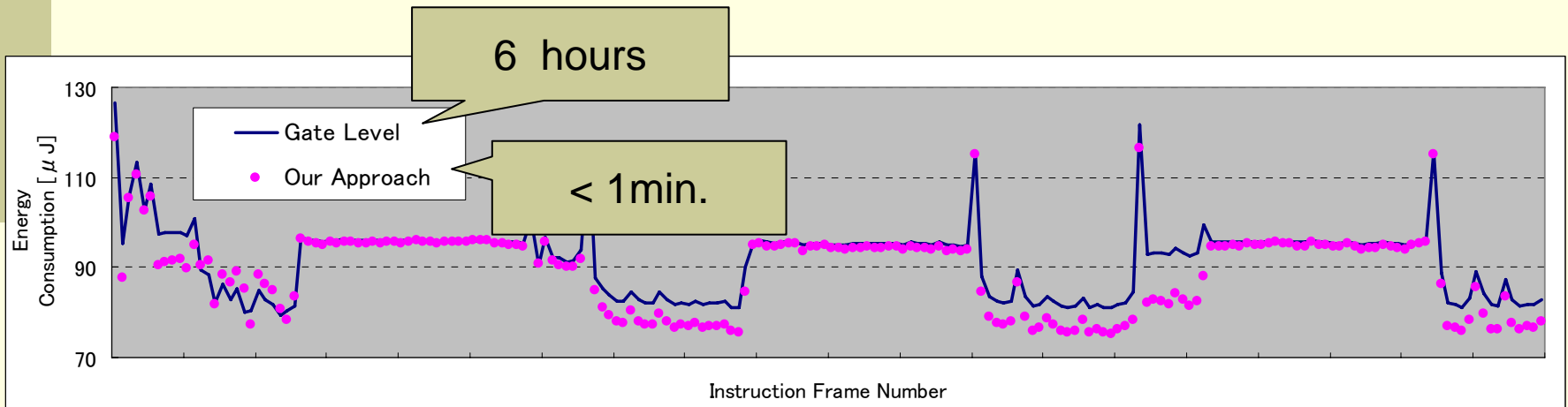
Use GDB as ISS

Fast, accurate, and processor-independent  
Instruction level energy estimation

# Experimental Result



Energy estimation for JPEG encoder executed on a M32R-II processor



Energy estimation for JPEG encoder executed on a SH3-DSP processor

# Related Work (1/2)

## High-level energy estimation

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### ■ Instruction-level modeling

- Energy estimation by instruction-set simulator
- Instruction level energy modeling by measuring the average power consumption of each instruction while executed in a loop

V. Tiwari, S. Malik, and A. Wolfe, "Power analysis of embedded software: a first step towards software power minimization," IEEE Tr. On VLSI, vol. 2, no. 4, pp. 437-445, Dec. 1994.

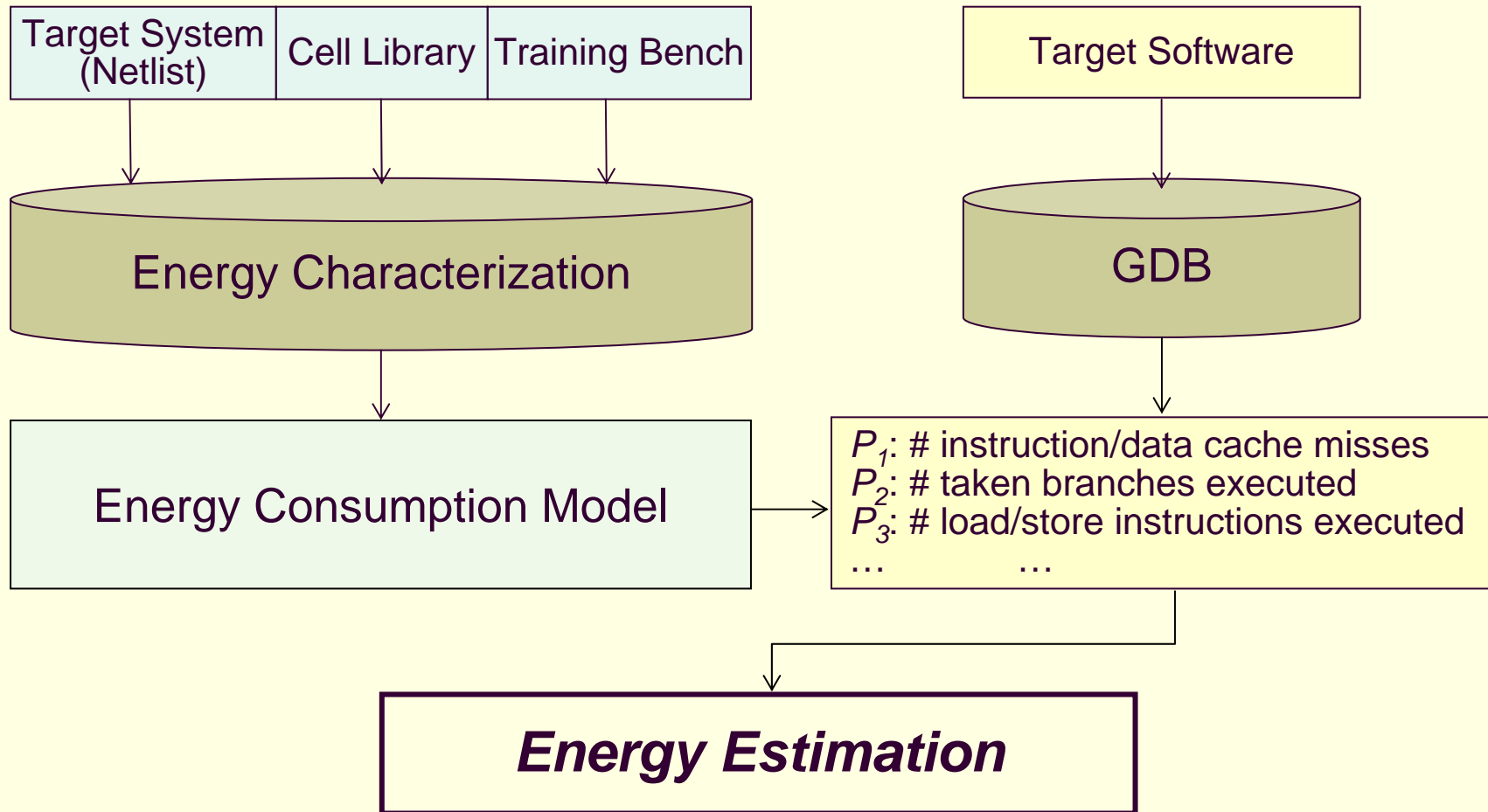
### ■ Structural modeling of the underlying hardware architecture

- Make power models by estimating capacitance on the circuit
- Keep track of which units are accessed per cycle by cycle-level performance simulation

D. Brooks, V. Tiwari, and M. Matonosi, "Wattch: A Framework for Architectural-Level Power Analysis and Optimization," in Proc. Of ISCA, pp. 84-94, June. 2000.



# Our Approach



# Related Work (2/2)

## Characterization-based energy estimation

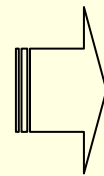
- Characterization-based macro-modeling
  - Regression analysis to model software energy
  - Model the energy consumption using linear expression

$$E = \sum_{j=1}^p c_j P_j$$

- $P_j$  : parameters of the model
- $c_j$  : corresponding coefficients
- $p$  : number of parameters

$$P = \begin{pmatrix} P_{1,1} & P_{1,2} & \dots & P_{1,p} \\ P_{2,1} & P_{2,2} & \dots & P_{2,p} \\ \dots & \dots & \dots & \dots \\ P_{n,1} & P_{n,2} & \dots & P_{n,p} \end{pmatrix}$$

$$E = \begin{pmatrix} E_1 \\ E_2 \\ \dots \\ E_n \end{pmatrix}$$



$$C = \begin{pmatrix} c_1 \\ c_2 \\ \dots \\ c_n \end{pmatrix} = [P^T P]^{-1} P^T E$$

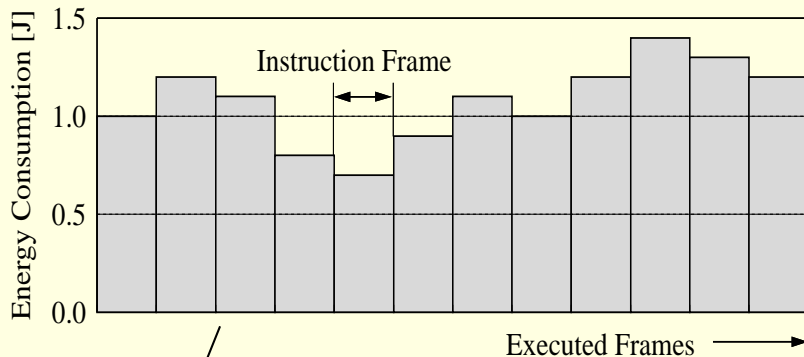
Evaluate set of parameters

Obtain the energy consumption by low-level estimator

Obtain coefficient using regression analysis

# Overview of Energy Characterization

- Energy consumption model based on linear expression
- Evaluate energy from each divided instruction frames



Extract by instruction-set simulation

Estimate energy at gate level

Instruction frame 1  
 Instruction frame 2  
 ...  
 Instruction frame n

$$\begin{array}{l}
 \Rightarrow E_1 \leftarrow E'_1 = c_1 P_{11} + c_2 P_{12} + c_3 P_{13} \dots \\
 \Rightarrow E_2 \leftarrow E'_2 = c_1 P_{21} + c_2 P_{22} + c_3 P_{23} \dots \\
 \vdots \\
 \Rightarrow E_n \leftarrow E'_n = c_1 P_{n1} + c_2 P_{n2} + c_3 P_{n3} \dots
 \end{array}$$

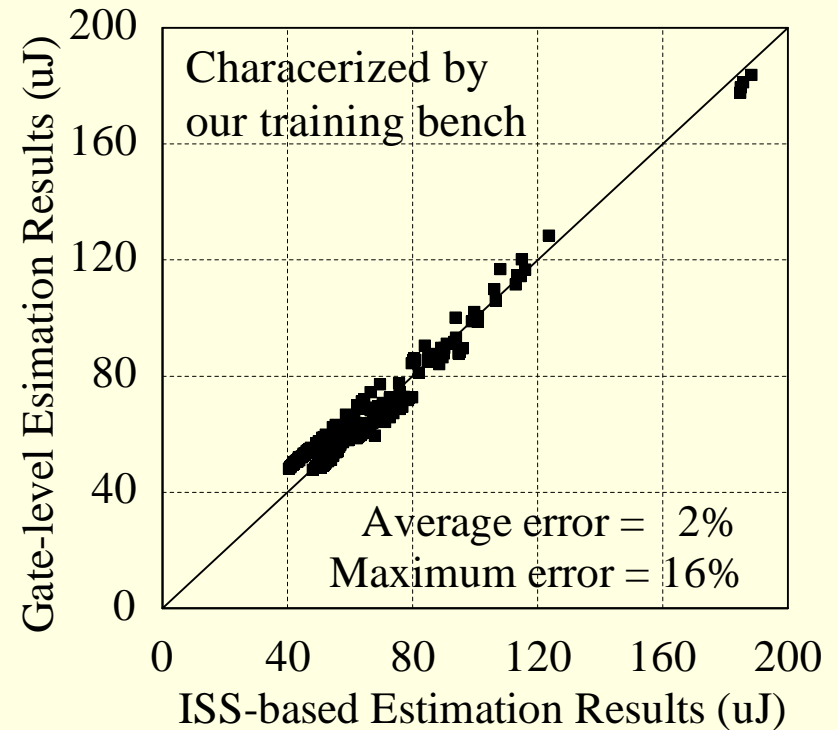
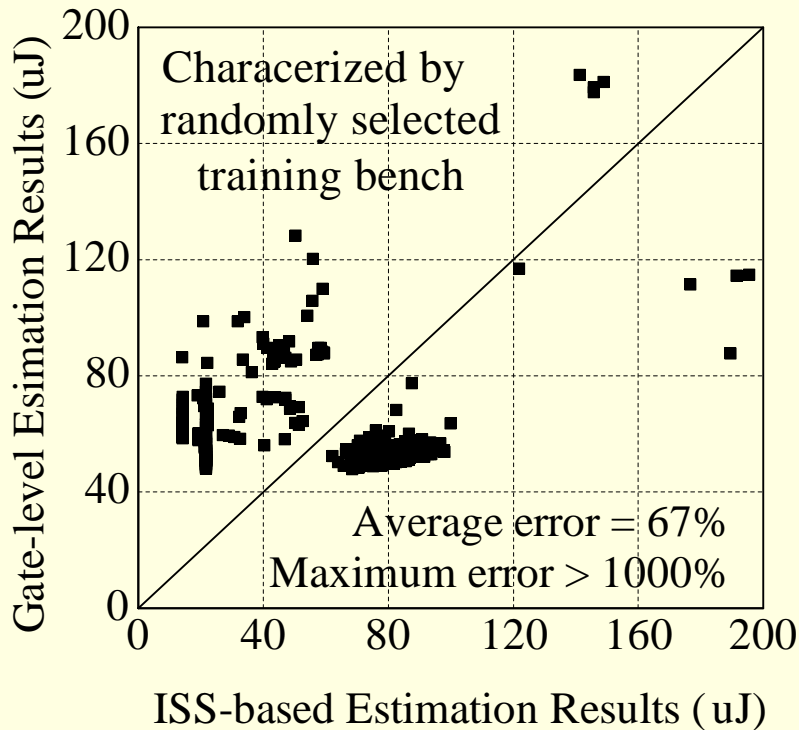
Solve the set of  $c_i$  which minimizes  $\sum_{i=1}^n |E'_i - E_i|$  10

# Error Sources of this characterization

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- Parameter set selection
- Non-linear effects
- Training bench
- ...

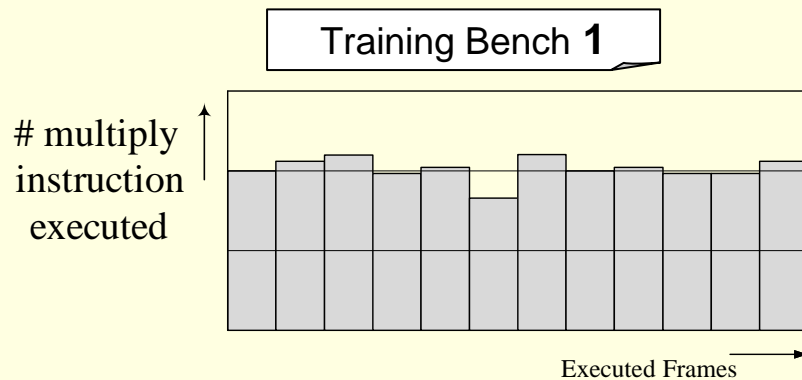
# Motivational Example



**Training bench dominates model accuracy !!**

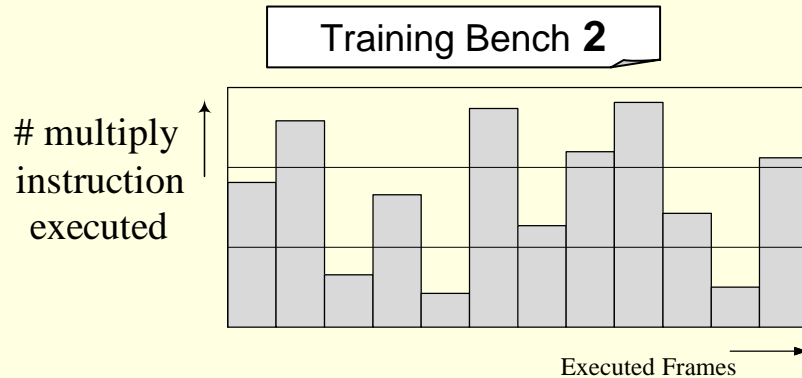
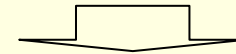
**What is expected for a 'good' training bench ?**

# Criteria on Training Bench (1/2)



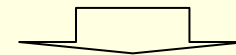
If parameter value of each frames is constant or mono-tone

Difficult to derive energy consumed by parameter



If parameter value of each frames is randomized

Suitable to derive energy consumed by parameter

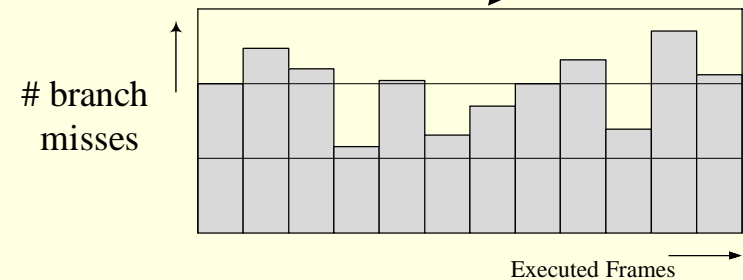
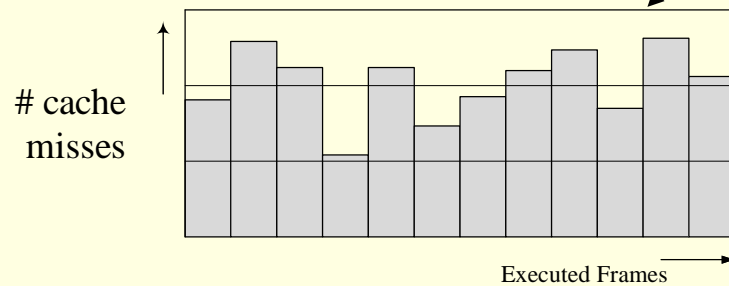


Criterion 1

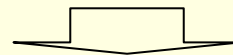
*Standard deviation of parameter value*

# Criteria on Training Bench (2/2)

$$E = c_1 P_1 + \dots + c_{cache\_miss} P_{cache\_miss} + c_{branch\_miss} P_{branch\_miss}$$



If correlation is strong between two parameters



Difficult to derive energy consumption by each parameters

Criterion 2

*Correlation between parameters*

# Training Bench Generation

## Template of Training Bench

- Execute power hungry instructions repeatedly
- Produce many cache misses
- Produce many RAW hazards
- Produce many pipeline stalls

Instruction Trace

- Standard deviations of parameter values  $\sigma$
- Correlation factors of two parameters  $\rho$

$\forall \sigma > 100$   
 $\forall \rho < 0.5$

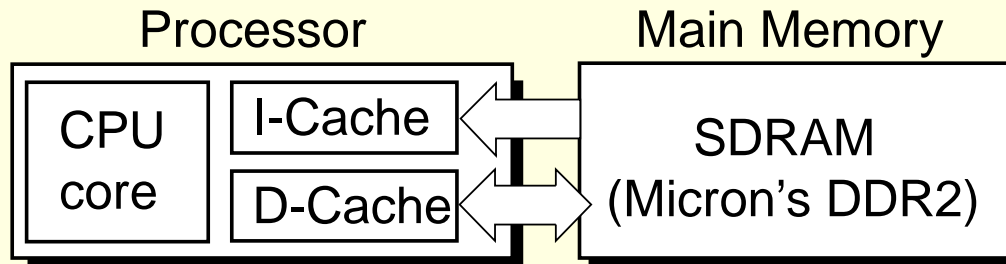
No

Yes



# Experiment

- Target system



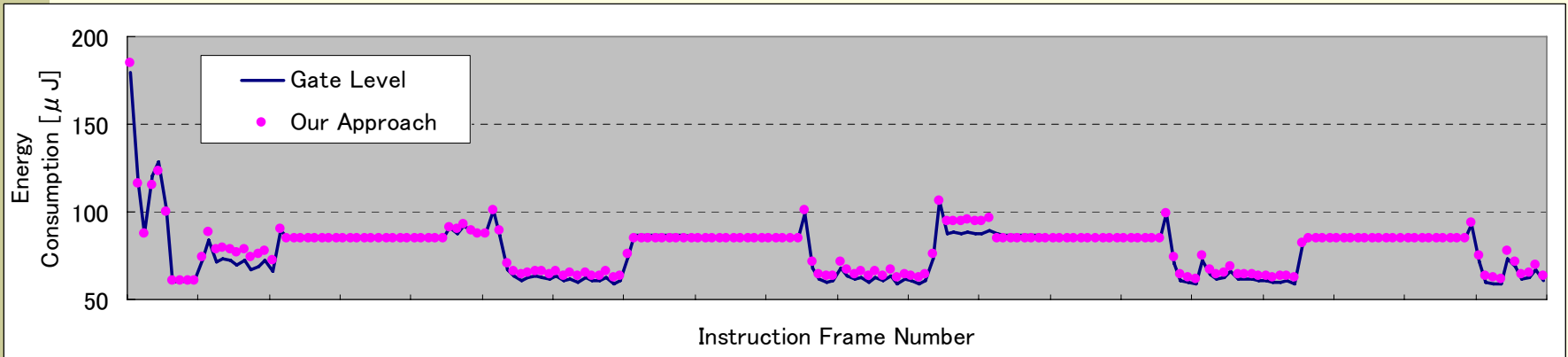
- Processors
  - M32R-II, SH3-DSP
- 0.18  $\mu$  m CMOS library

# Experimental Result - Energy estimation error

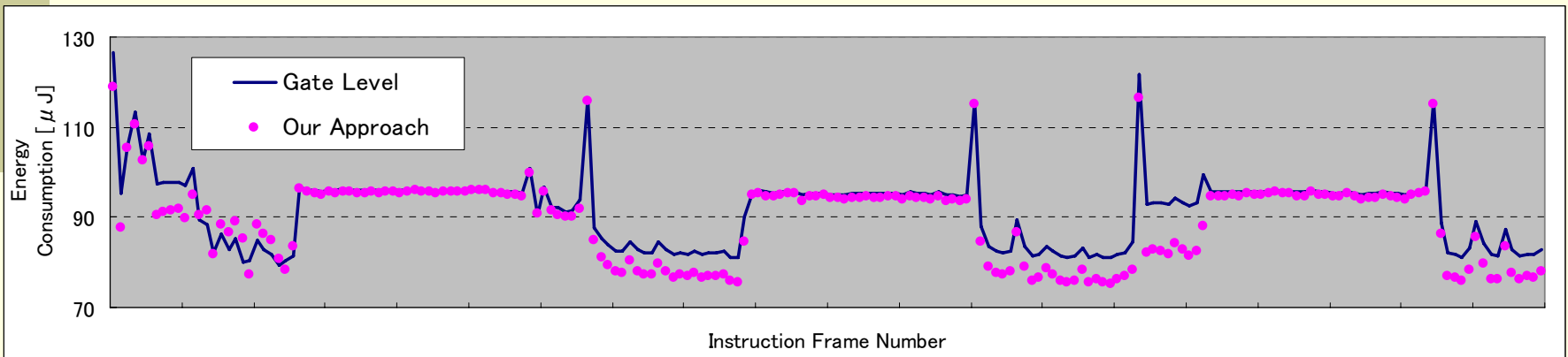
	M32R-II		SH3-DSP	
	Average Error	Maximum Error	Average Error	Maximum Error
JPEG	2.70 %	10.32 %	3.17 %	11.89 %
JPEG_O	6.09 %	16.46 %	6.33 %	10.02 %
MPEG2	1.54 %	3.97 %	1.32 %	3.41 %
MPEG2_O	1.78 %	5.15 %	1.31 %	5.63 %
compress	5.00 %	6.41 %	5.73 %	10.84 %
compress_O	4.35 %	7.18 %	1.73 %	15.15 %
FFT	1.55 %	6.87 %	1.27 %	3.26 %
FFT_O	1.45 %	5.59 %	1.15 %	4.75 %
DCT	1.42 %	8.58 %	1.12 %	2.20 %
DCT_O	1.47 %	8.07 %	1.51 %	3.04 %
Total	<b>2.74 %</b>	<b>16.46 %</b>	<b>2.47 %</b>	<b>15.15 %</b>

Compared to the gate level estimation  
 \*\_O : compiled with a "-O3" optimize option

# Experimental Result



Energy estimation for JPEG encoder executed on a M32R-II processor



Energy estimation for JPEG encoder executed on a SH3-DSP processor

# Summary

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- Proposed energy characterization framework for processor-based embedded system
- Error is on an average 3% and worst case 16%
- Future work
  - Compare result to board level measurement
  - Extend current work to multi-core processor systems
  - Extend to systems running on RTOS

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***Thank You !***