ESE5320: System-on-a-Chip Architecture

Day 23: November 22, 2022

Energy

1

Today

Energy

- Part 1
  - Today's bottleneck
  - What drives
- Part 2: Architecture and Energy
  - Processors, FPGAs, accelerators
- Part 3:
  - How does parallelism impact energy?

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Message

- Energy dominates
  - Including limiting performance
- Make memories small and wires short
  - Small memories cost less energy per read
- Accelerators reduce energy
  - Compared to processors
- Can tune parallelism to minimize energy
  - Typically, the more parallel implementation costs less energy

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Energy

- Growing domain of portables
  - Less energy/op → longer battery life
- Global Energy Crisis
- Limit to the power our computers/devices can dissipate (we can provide)
  - Reduce E/op
    - → increase compute when power limited
  - Scaling
    - Power density **not** transistors limit sustained ops/s
  - Server rooms
    - Cost-of-ownership **not** dominated by Silicon
    - Cooling, Power bill

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Preclass 1--4

- 200K gates/mm^2
- 5*10^{-15} J/gate switch
- Gates on 1cm^2
- Energy to switch all?
- Power at 1GHz?
- Fraction can switch with 10W/cm^2 power budget?

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Challenge: Power

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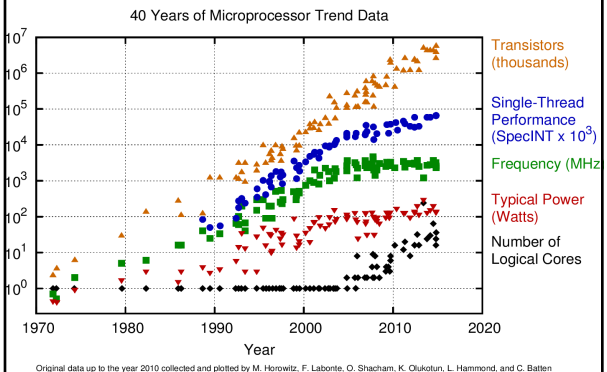
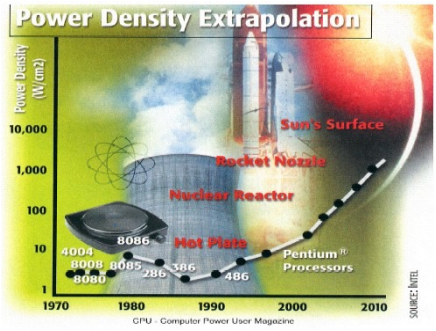
Origin of Power Challenge

- Limited capacity to remove heat
  - ~100W/cm^2 force air
  - 1-10W/cm^2 ambient
- Transistors per chip grow at Moore's Law rate = (1/F)^2
- Energy/transistor must decrease at this rate to keep constant power density
- P/tr $\propto$ CV^{2}f
- E/tr $\propto$ CV^2
  - …but V scaling more slowly than F

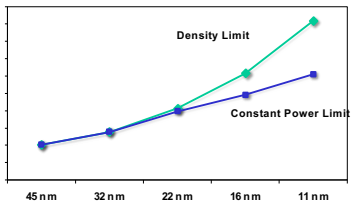


Intel Power Density



Impact

Power Limits Integration



Source: Carter/Intel

Impact

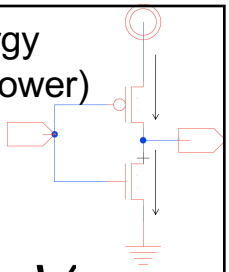
- Power density is limiting scaling
  - Can already place more transistors on a chip than we can afford to turn on!
- Power is potential challenge/limiter for all future chips.
  - Only turn on small percentage of transistors?
  - Operate those transistors at much slower frequency?

Energy

$$E_{total} = E_{switch} + E_{leak}$$

- Dynamic – Switching Energy (Power)
- Static – Leakage Energy (Power)

Leakage Energy (Static Energy, Power)



- I_{leak}
  - Subthreshold leakage
  - (possibly) Gate-Drain leakage

$$P_{leak} = I_{leak} \times V$$

$$E_{leak} = P_{leak} \times T$$

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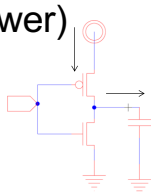
Switching Energy (Dynamic Energy, Power)

$$E_{switch} \propto \alpha CV^2$$



$$Q = CV = \int I(t)dt$$

$$E = \int I(t)V_{dd}dt$$

- Charge/discharging gate and load
- C – driven by architecture
- V – today, driven by variation, aging
- α – probability will switch; driven by architecture, coding/information

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Energy

$$E_{total} = E_{switch} + E_{leak}$$

$$E_{switch} \propto \alpha CV^2$$

$$E_{leak} = I_{leak} \times V \times T$$

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Voltage

$$E_{switch} \propto \alpha CV^2 \quad E_{leak} = I_{leak} \times V \times T$$

- We can set voltage
- Reducing voltage
  - Reduces E_{switch}
  - Increases delay → cycle time, T (freq=1/T)
    - Reduce performance (not run full freq.)
    - Increases leakage E_{leak}

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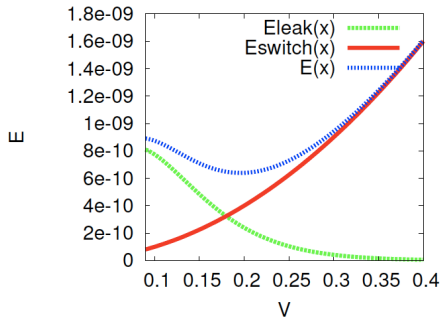
Total Energy vs. Voltage



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Switching Energy

$$E_{switch} \propto \alpha CV^2$$

- C – driven by architecture
  - Also impacted by variation, aging
- V – today, driven by variation, aging
- α – probably a node will switch; driven by architecture, information

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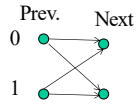
Data Dependent Activity

- Consider an 8b counter
  - How often do each of the following switch?
    - Low bit?
    - High bit?
  - Average switching across all 8 output bits?
- Assuming random inputs
  - Activity (switching probability) at output of xor4?
    - Hint: probability of output of xor4 being 0? 1?
  - Activity at output of nand4?

Gate Output Switching (random inputs)



Pswitch=P(0@i)*P(1@i+1)
+P(1@i)*P(0@i+1)

Conclude

- Not all gates (output nodes) switch at same rate

Switching Energy

$$E_{switch} = \left(\sum_i \alpha_i C_i\right) V^2$$

C_i == capacitance driven by each gate (including wire)

Switching Rate (α_i) Varies

- Different logic (low/high bits, gate type)
- Different usage
  - Gate off unused functional units
- Data coded
- Entropy in data
- Average α 5--15% plausible

$$E_{switch} = \left(\sum_i \alpha_i C_i\right) V^2$$

Switching Energy

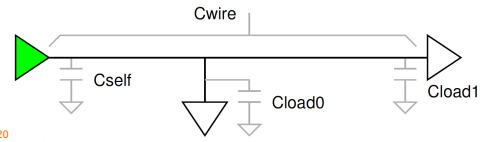
$$E_{switch} \propto \alpha C V^2$$

- C – driven by architecture
- V – today, driven by variation, aging
- α – driven by architecture, information

Wire Driven

$$E_{switch} = \left(\sum_i \alpha_i C_i\right) V^2$$

- Gates drive $C_i = C_{self} + C_{wire} + C_{load}$
  - Self
  - Inputs to other gates
  - Wire routing between self and other gates
- Typically: $C_{wire} > C_{self} + C_{load}$



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Wire Capacitance

- How does wire capacitance relate to wire length?

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Wire Capacitance

- $C = \varepsilon A/d = \varepsilon W * L_{wire}/d = C_{unit} * L_{wire}$
- Wire capacitance is linear in wire length
- E.g. 1.7pF/cm (preclass)
- Remains true if buffer wire
  - Add buffered segment at fixed lengths
  - [different use of word *buffer* than normal in this class – here we're talking about adding a repeater to perform electrical signal restoration]

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Wire Driven Implications

- Care about locality
  - Long wires are higher energy
  - Producers near consumers
  - Memories near compute
  - Esp. for large α_i's

$$E_{switch} = \left(\sum_i \alpha_i C_i\right) V^2$$

- Care about size/area
  - Reduce (worst-case) distance must cross
- Care about minimizing data movement
  - Less data, less often, smaller distances
- Care about size of memories

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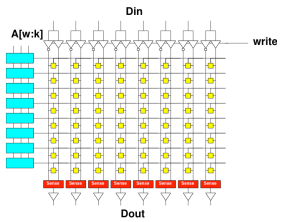
Preclass 5

- Primary switching capacitance in wires
- C: How does energy of a read grow with capacity (N) of a memory bank?
- D: Energy per bit?



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Memory Implications

- Memory energy can be expensive
- Small memories cost less energy than large memories
  - Use data from small memories as much as possible
- Cheaper to re-use data item from register than re-reading from memory

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Energy

$$E_{total} = E_{switch} + E_{leak}$$

$$E_{switch} = \left(\sum_i \alpha_i C_i\right) V^2$$

$$E_{leak} = \left(\sum_i E_{leak_i}\right) V \times T$$

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Architectural Implications

Part 2

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Component Numbers

Energy Per Operation (0.13μm, 1.2V)

TABLE 1

Operation	Energy
32-bit arithmetic operation	5 pJ
32-bit register read	10 pJ
32-bit 8KB RAM read	50 pJ
32-bit traverse 10mm wire	100 pJ
Execute instruction	500 pJ

[Dally, March 2004 ACM Queue]

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Component Numbers

- Processor instruction 100x more than arithmetic
- Register read 2x
- RAM read 10x
- Why processor instruction > arith operation?

Energy Per Operation (0.13μm, 1.2V)

TABLE 1

Operation	Energy
32-bit arithmetic operation	5 pJ
32-bit register read	10 pJ
32-bit 8KB RAM read	50 pJ
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Execute instruction	500 pJ

[Dally, March 2004 ACM Queue]

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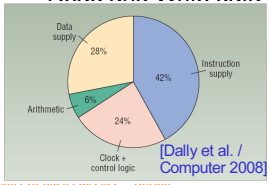
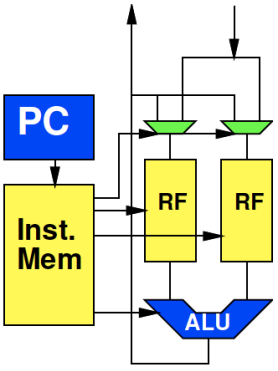
Processors and Energy

- Very little energy into actual computation
- Determine and Fetch Instruction
- Read and Write data



[Dally et al. / Computer 2008]



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ARM Cortex A9

Estimate find: 0.5W at 800MHz in 40nm

- $0.5/0.8 \times 10^{-9}$ J/instr
- ~600pJ/instr
- Scale to 28nm
  - maybe 0.7*600—0.5*600
  - 300—400pJ/instr ?
- Is superscalar w/ Neon, so not as simple a processor as previous example

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Zynq (7-series, 28nm)

Operation	PL Resource	ARM A9 Resource	ARM A9 energy/OP (pico Joules or mW/GOP/sec)	PL energy/OP (pico Joules op mW/GOP/sec)
Logical Op of 2 var	LUT/FF	ALU		1.3
32-bit ADD	LUT/FF	ALU		1.3
16x16 Mult	DSP	ALU		8.0
32-bit Read/Write register	LUTRAM	L1		1.4
32-bit Read/Write AXI register	LUT/FF	AXI		30
32-bit Read/Write local RAM	BRAM	L2		23.7/17.2
32-bit Read/Write OCM	AXI/OCM	CPU/OCM		44
32-bit Read/Write DDR3	AXI/DDR	CPU/DDR		541/211

- ARM A9 instruction 300—400pJ
- ARM A9 L1 cache read 23pJ

Xilinx UG585 – Zynq TRM

Compare

- Assume ARM Cortex A9 executes 4x32b Neon vector add instruction for 300pJ
- Compare to 32b adds on FPGA?

Operation	PL Resource	ARM A9 Resource	ARM A9 energy/OP (pico Joules or mW/GOP/sec)	PL energy/OP (pico Joules op mW/GOP/sec)
Logical Op of 2 var	LUT/FF	ALU		1.3
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32-bit Read/Write DDR3	AXI/DDR	CPU/DDR		541/211

Compare

- Assume ARM Cortex A9 executes 4x16b Neon vector multiply instruction for 300pJ
- Compare to 16x16 multiplies on FPGA?

Operation	PL Resource	ARM A9 Resource	ARM A9 energy/OP (pico Joules or mW/GOP/sec)	PL energy/OP (pico Joules op mW/GOP/sec)
Logical Op of 2 var	LUT/FF	ALU		1.3
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Programmable Datapath

- Performing an operation in a pipelined datapath can be orders of magnitude less energy than on a processor
  - ARM 300pJ vs. 1.3pJ 32b add
  - Even neon 300pJ vs. 4x1.3pJ for 4x32b add
  - 300pJ vs. 4x8pJ for 4 16x16b multiplies

Zynq

Operation	PL Resource	ARM A9 Resource	ARM A9 energy/OP (pico Joules or mW/GOP/sec)	PL energy/OP (pico Joules op mW/GOP/sec)
Logical Op of 2 var	LUT/FF	ALU		1.3
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- Reading from OCM order of magnitude less than from DRAM
- …and BRAM half that

Xilinx UG585 – Zynq TRM

FPGA vs. Std Cell Energy

- 90nm
- FPGA: Stratix II
- STMicro CMOS090

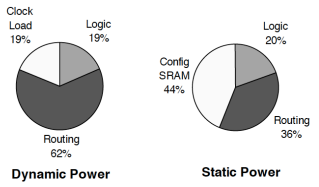
TABLE VI
DYNAMIC POWER CONSUMPTION RATIO (FPGA/ASIC)

Name	Method	Logic Only	Logic & DSP	Logic & Memory	Logic, Memory & DSP
booth	Sim	26			
rs_encoder	Sim	52			
cordic18	Const	6.3			
cordic8	Const	5.7			
des_area	Const	27			
des_perf	Const	9.3			
fir_restruct	Const	9.6			
mac1	Const	19			
aes192	Sim	12			
fir3	Const	12	7.5		
diffeq	Const	15	12		
diffeq2	Const	16	12		
molecular	Const	15	16		
rs_decoder1	Const	13	16		
rs_decoder2	Const	11	11		
atm	Const			15	
aes	Sim			13	
aes_inv	Sim			12	
ethernet	Const			16	
serialproc	Const			16	
fir24	Const				5.3
pipe5proc	Const				8.2
raytracer	Const				8.3
Geomean		14	12	14	7.1

[Kuon/Rose TRCADv26n2p203--215 2007]

FPGA Disadvantage to Custom

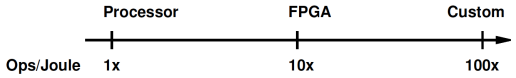
- Interconnect Energy
  - Long wires → more capacitance → more E
  - Switch Energy is an overhead



[Tuan et al./FPGA 2006]

Simplified Comparison

- Processor two orders of magnitude higher energy than custom accelerator
- FPGA accelerator in between
  - Order of magnitude lower than processor
  - Order of magnitude higher than custom



Accelerators save Energy

- Customized accelerators save energy
  - Even when built on FPGA
- Recall: can put more transistors on chip than can afford to turn on
- Opportunity to spend extra transistors to save energy and increase performance
  - Even if don't use accelerator continuously
- Opportunity: Area-energy tradeoff

Apple A14 Bionic

- 88mm^2, 5nm
- 11.8 Billion Tr.
- iPhone 12
- 6 ARM cores
  - 2 fast (2.9--3GHz)
  - 4 low energy
- 4 custom GPUs
- 16 Neural Engines
  - 11 Trillion ops/s?

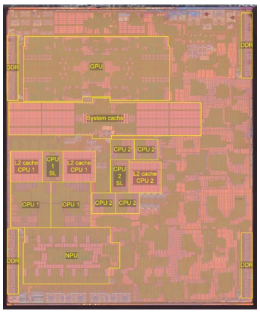


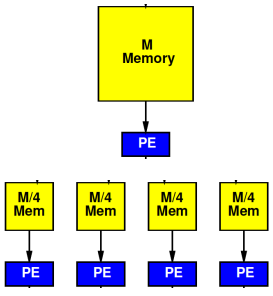
Image from https://www.extremetech.com/computing/318715-comparison-of-apple-m1-a14-shows-differences-in-soc-design
details: https://www.tomshardware.com/news/apple-a14-bionic-revealed
https://www.anandtech.com/show/16226/apple-silicon-m1-a14-deep-dive/2

Parallelism and Energy

Part 3

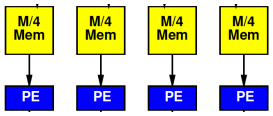
Preclass 6

- Energy
  - Per read from M=10^6 memory?
  - Per read from 10^6/4 memory?



Local Consumption

- To exploit, we must consume the data local to the memory.

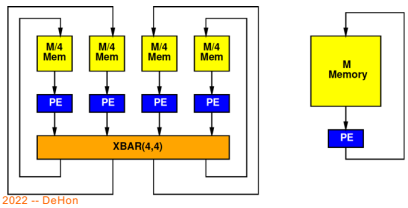


Inter PE Communication

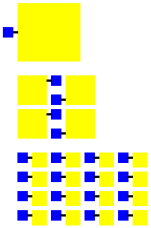
- May need to communicate between parallel processing elements [PEs] (and memories)
- Must pay for energy to move data between PEs

Preclass 7

- Energy: Read 4 memories 10^6/4, route 4x4 crossbar, write 4 10^6/4 memories?
- Energy: 4 reads from 10^6 memory, 4 writes from 10^6 memory?



Parallel Larger



- More parallel design
  - Has more PEs
  - Adds interconnect

→Total area > less parallel design

- More area → longer wires → more energy in communication between PEs
- Could increase energy!

Continuum Question

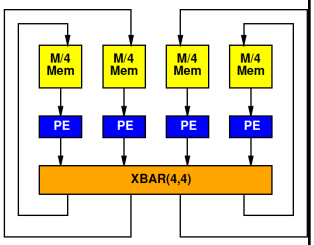
- Where do we minimize total energy?
  - Both memory and communication
- Design axis P – number of PEs
  - What P minimizes energy?

Simple Model

- E_{mem}=sqrt(M)
- Communication = E_{xbar}(I,O)=4*I*O
- P Processors
- N total data
- Possibly communicate each result to other PEs

Simple Model: Memory

- Divide N data over P memories
- E_{mem}=sqrt(N/P)
- N total memory operations
- Memory energy: N*sqrt(N/P)
- Memory energy decrease with P



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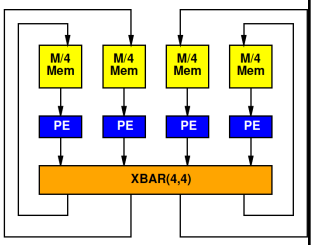
Simple Model: Communication

- Crossbar with P inputs and P outputs
- E_{xbar}=4*P*P
- Crossbar used N/P times
- Crossbar energy: 4*N*P
- Communication energy increase with P



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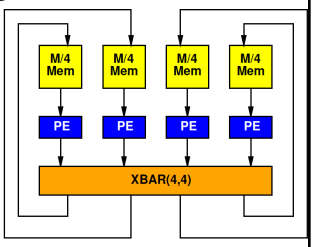
Simple Model

$$N \times \sqrt{\left(\frac{N}{P}\right)} + N \times 4 \times P$$

$$N \times \left(\sqrt{\left(\frac{N}{P}\right)} + 4 \times P\right)$$



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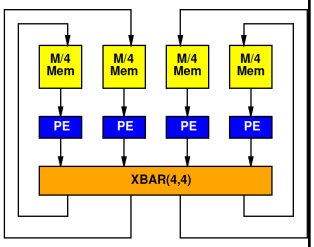
Preclass 8

- For $N=10^6$

$$N \times \left(\sqrt{\left(\frac{N}{P}\right)} + 4 \times P\right)$$

- Per operation becomes:

$$\frac{10^3}{\sqrt{P}} + 4P$$



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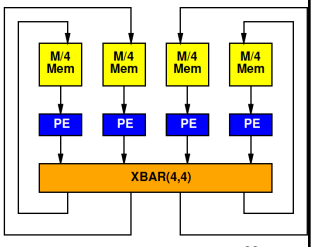
Preclass 8

- Energy for:
  - P=1
  - P=4
  - P=100
- Energy minimizing P?
  - Energy?

$$\frac{10^3}{\sqrt{P}} + 4P$$



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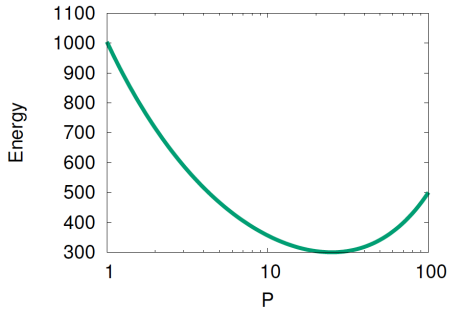
Graph



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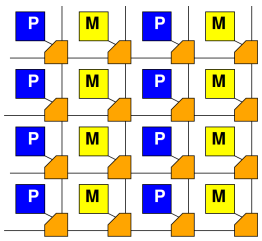
High Locality

- If communication is local, don't need crossbar
  - Remember Rent's Rule
- Communication energy scales less than P^2
- Can scale as low as P



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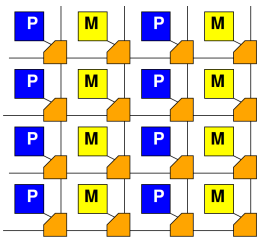
Model for High Locality

- E_{comm}=constant
- E_{comm}=10
- Total comm:
  N*10

$$N \times \left(\sqrt{\left(\frac{N}{P} \right)} + 10 \right)$$



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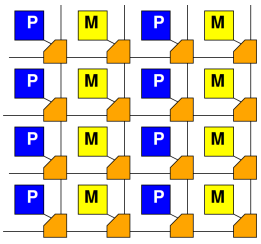
Preclass 9

- What is energy minimizing P?

$$\frac{10^3}{\sqrt{P}} + 10$$



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Task Locality Matters

- Optimal P (processors) depends on communication locality (Rent Expontent p)
  - Very local problems (p<0.5) always benefit from parallelism
  - Highly interconnected problems (p>0.5) must balance energies → intermediate parallelism

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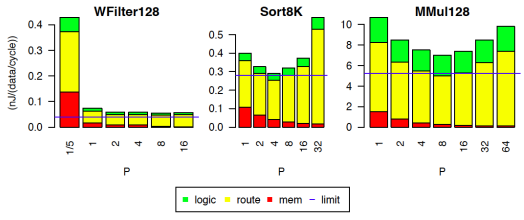
Tune Parallelism: Stratix-IV



[Kadric, FPGA 2015]

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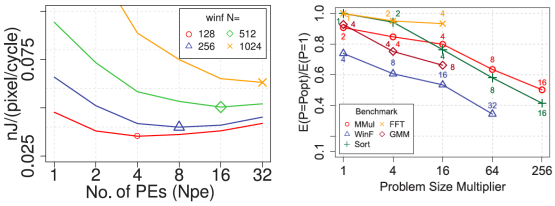
PE Scaling with Problem Size



[Kadric, TRETS 2016]

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Power vs. Energy

- Notice: main comparisons are energy for operation or task
  - Not power
- Power is rate of energy use
  - Can slow down clock to reduce power
    - But leaves Energy unchanged
  - Power alone doesn't tell us energy requirement or energy efficiency
    - Need to also know time
      - Energy ~= Power * Time
    - Sometimess see Gops/W → Ops/J → energy metric

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Big Ideas

- Energy dominance
- With power-density budget
  - The most energy efficient architecture delivers the most performance
- Make memories small and wires short
- SoC, accelerators reduce energy by reducing processor instruction execution overhead
- Parallel design exploit locality→reduce energy
- Optimal parallelism for problem
  - Driven by communication structure, size

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Admin

- Feedback (including P3)
- Tuesday is Virtual Thursday
  - Thursday office hours
- No class on Wed.
  - This Wed. is a Virtual Friday
- Happy Thanksgiving!
- P4 due next Friday
- Reading for Monday on web

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