International Conference on Supercomputing 2002 Tutorial: Minimally Clocked Microprocessor Design

Diana Marculescu (CMU), Dave Albonesi (Rochester), Pradip Bose (IBM)

Schedule

- **8:30-9:30 (Diana Marculescu)**
  - Trends and issues in clock distribution
  - How much asynchrony do we want?
  - Motivation for GALS, synchronization issues, deadlock prevention, possible inter-clocking domain communication schemes
  - GALS processors: power/performance evaluation
- **9:30-9:45 Break**
- **9:45-10:45 (Dave Albonesi)**
  - GALS processors: power/performance evaluation (cont'd)
  - Workload characterization and impact on the use of fine grain speed/voltage scaling
- **10:45-11:00 Break**
- **11:00-12:00 (Pradip Bose)**
  - Case study - LPX, an IPCMOS based processor
- **12:00-12:20 (Diana Marculescu)**
  - Looking in the crystal ball: Where will GALS be used?
  - Concluding remarks
- **12:20-12:30 Q&A**

But first… What is “minimally clocked”?

What is minimal clocking?…

- **Asynchrony in (almost) any shape or form…**
- **… But mostly:**
  - Globally Asynchronous, Locally Synchronous (GALS) designs
  - Self-timed logic within fully synchronous systems (Locally Asynchronous, Globally Synchronous)
  - Not fully asynchronous
- **Thus, "minimally clocked" encompasses design styles that**
  - Do not have a global timing reference
  - Rely on synchronization mechanisms
  - Are not fully asynchronous

Why minimally clocked?

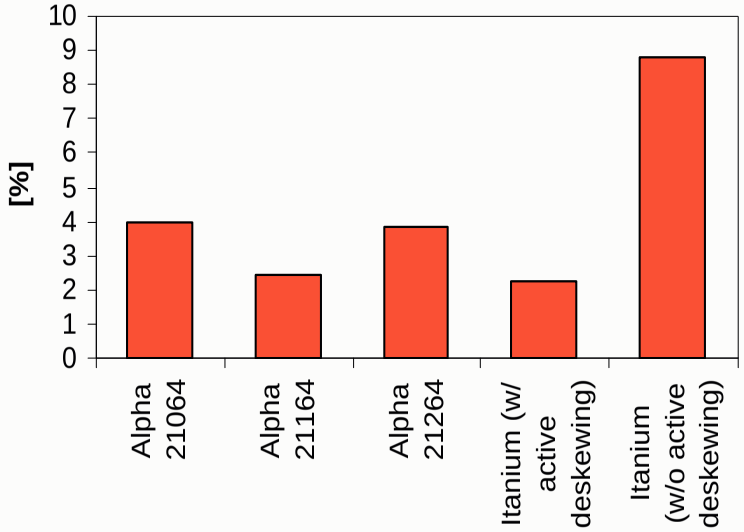
- **Current design roadblocks:**
  - Increasing power density
  - Increasing design complexity
- **Shortening time-to-market require:**
  - Design and verification tools and methodology
  - Solutions for design testability and reliability
- **Drivers for minimally clocking:**
  - Design reuse (IPs independently designed)
  - Minimize design effort for global clock distribution
  - Allow fine-grain application-driven adaptability (voltage and speed scaling)

Trends and issues in clock distribution

Global clock distribution issues

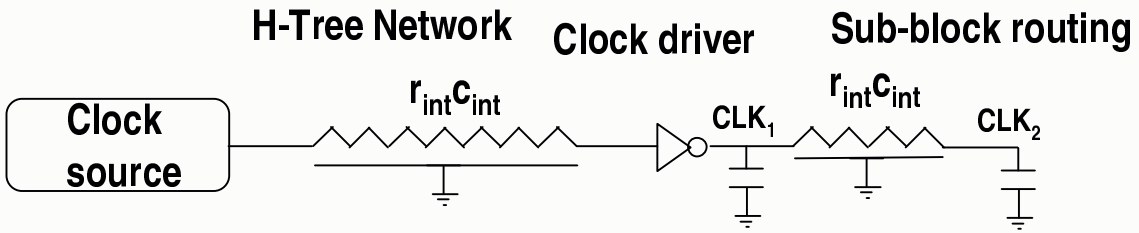
- **Global clock distribution is getting more difficult**
  - Larger die size and device count
  - Higher clock speed
  - Increasing clock power consumption (30-40% of total power)

- **Clock skew has become a large part of the cycle time**



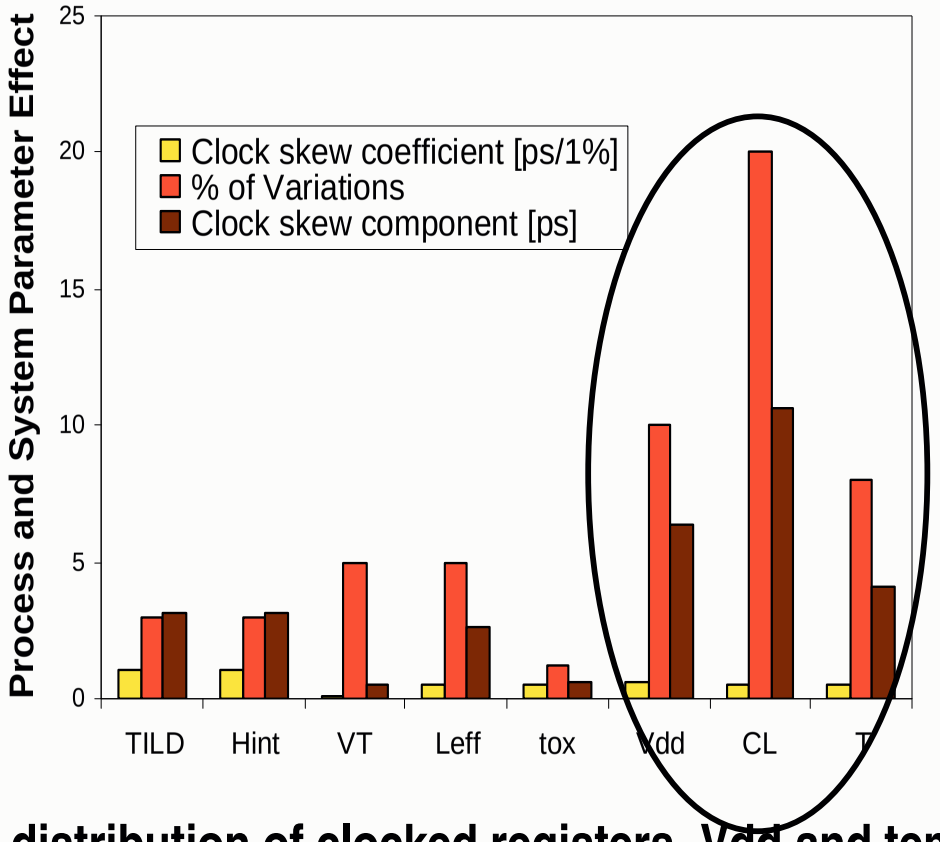
Clock skew

- **Case study: H-tree**
- **Skew components:**
  - Interconnect delay from clock source thru the H-tree to the driver
  - Transistor delay of the sub-block driver
  - Internal wire routing delay within the sub-block from clock driver to registers – also called *internal clock skew*



- **The first 2 components are most affected by physical parameter variation**

Clock skew components



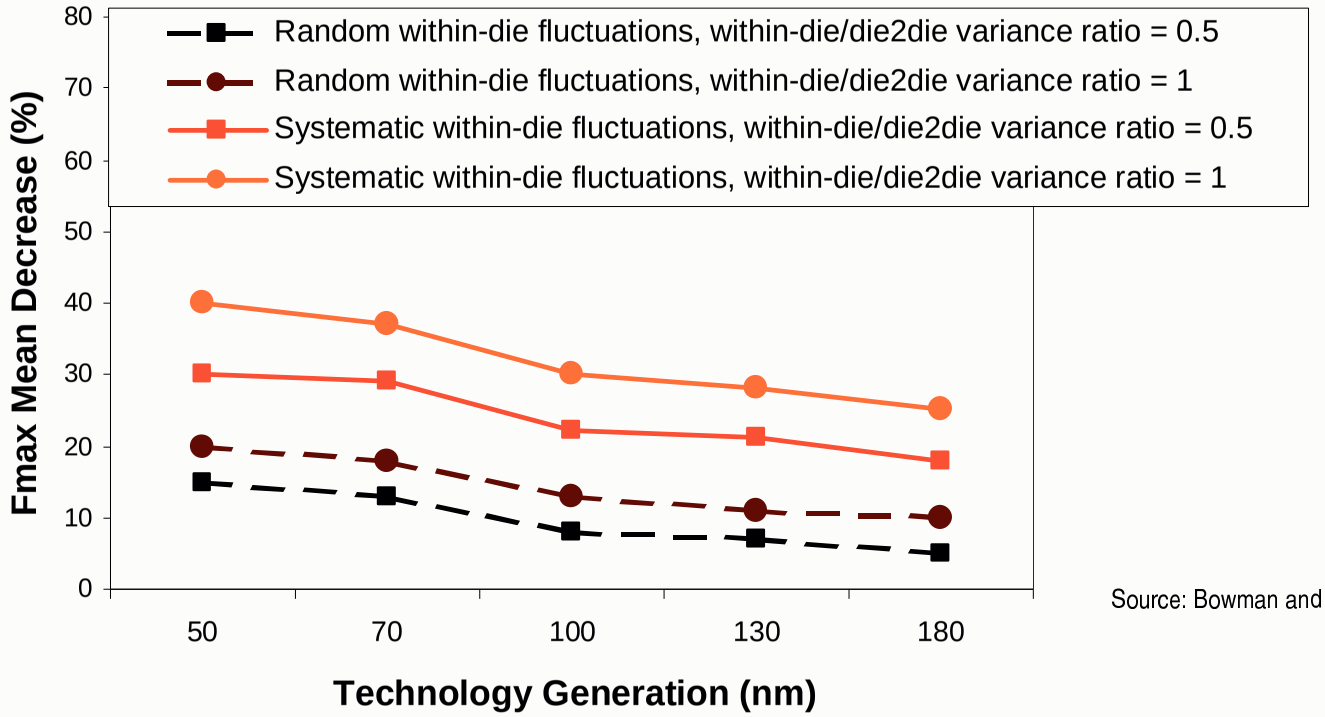
Source: Zarkesh-Ha, Mule and Meindl, 1999

- **Non-uniform distribution of clocked registers, Vdd and temperature may have the highest impact on clock skew**
  - Assumptions: 20,000 clocked registers and Alpha's temperature map

How bad can the variation be?

- **Clocked pipeline registers**
  - Worst case variations of up to a factor of 3
  - May translate into 20% variation among sub-block loading capacitances
- **Temperature variations**
  - Some structures are hotter than others…
  - …And thus induce further increase in clock skew

Adverse effect of process variation

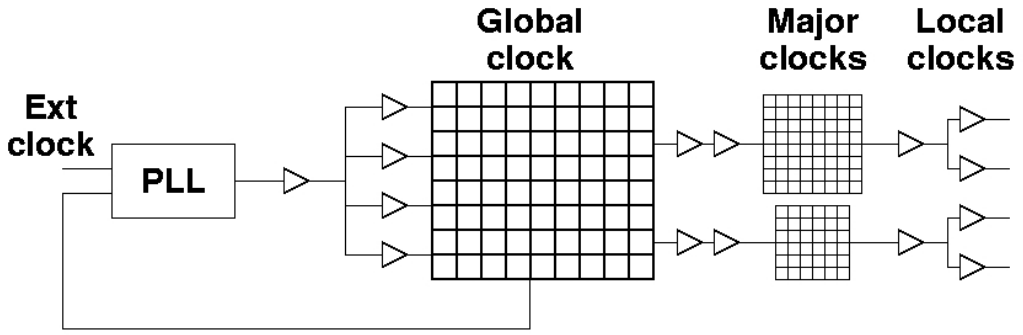


Source: Bowman and Meindl, 2001

- **Significant effect on maximum clock speed**
  - Up to 30-40% reduction in clock speed for 0.05 um technology
- **Need design styles that reduce these variations**

Current solutions for clock distribution

- **Traditionally done with PLL, metal grids and H-trees**
  - Requires lot of die area, power, design effort
- **Nowadays, clock distribution is done hierarchically**
  - Global clock and major clocks
  - Deskewing circuits – may incur a lot of design effort and silicon



- **ITRS 2001 (SIA Roadmap)**
  - GALS design style for alleviating clock distribution problems

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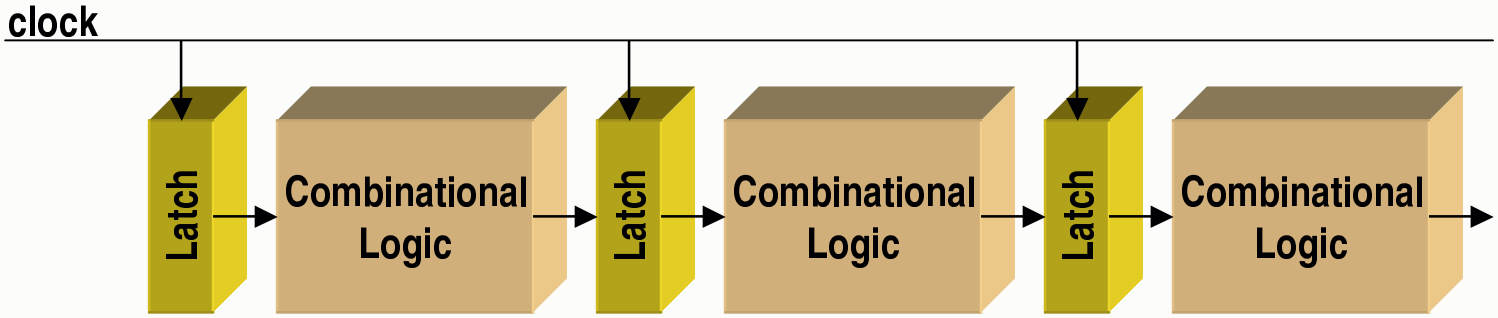
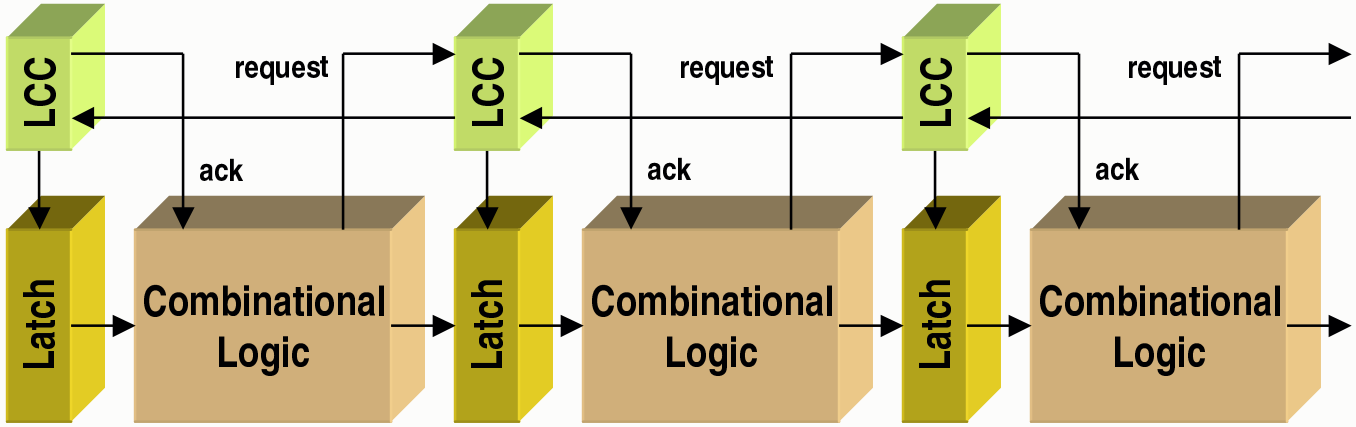
How much asynchrony do we want?

Synchronous vs. asynchronous pipelines

- Synchronous

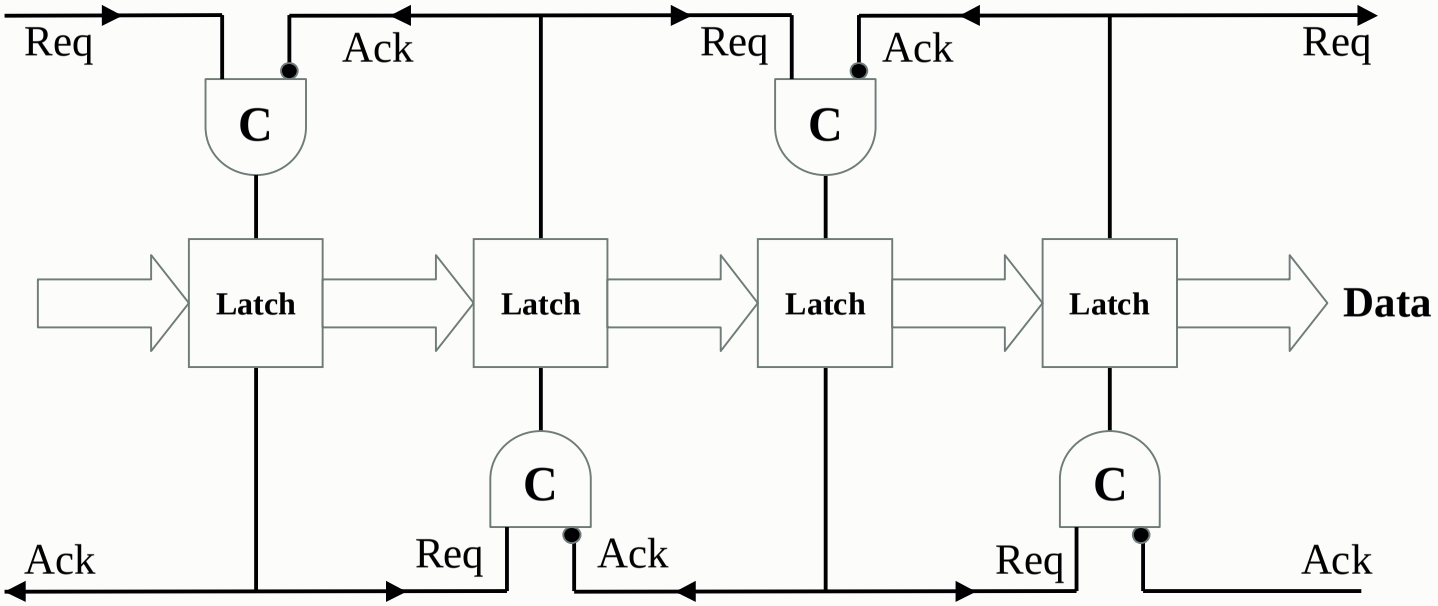


- Asynchronous

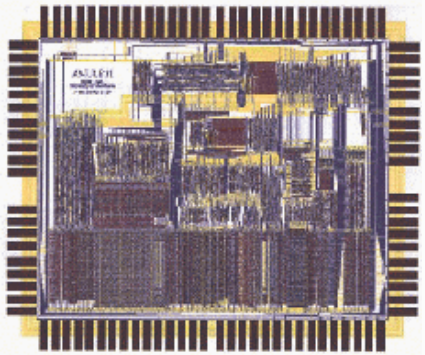


Micropipelines

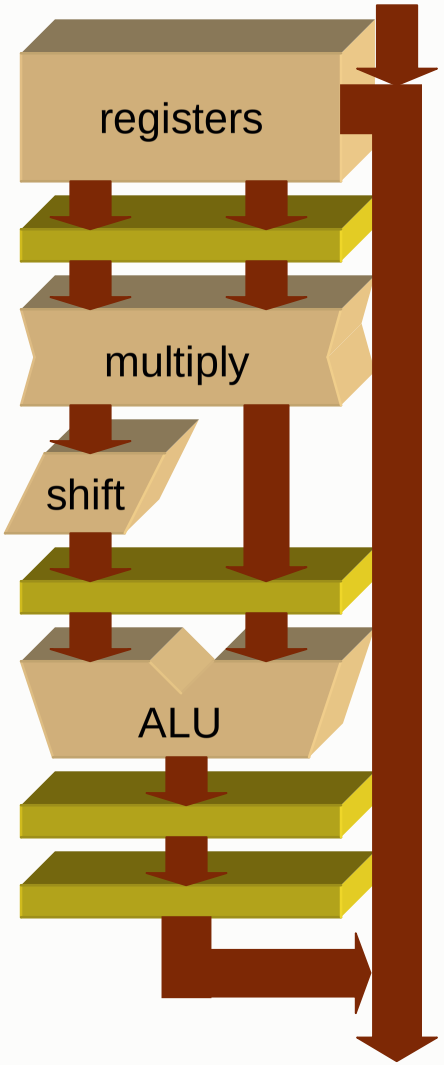
- Introduced in 1989 [Sutherland, CACM 1989, Turing Award Lecture]
- Handshaking based on transition signaling instead of standard logic levels



AMULET1

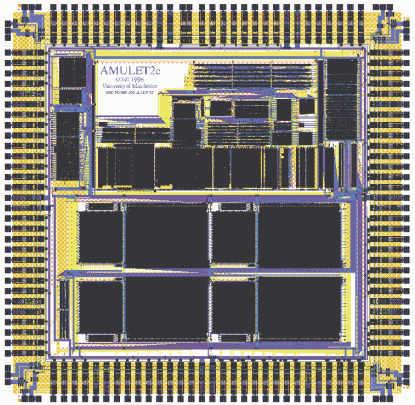


Source: http://www.cs.man.ac.uk/amulet/index.html



- **Designed between 1990-1993**
- **No bypassing, relies on register locking mechanism**
- **Each functional unit is micropipelined**
- **AMULET1 Lessons**
  - Micropipelines good on chip, hard to debug at board level
  - Execution pipeline deeper than needed

AMULET2e



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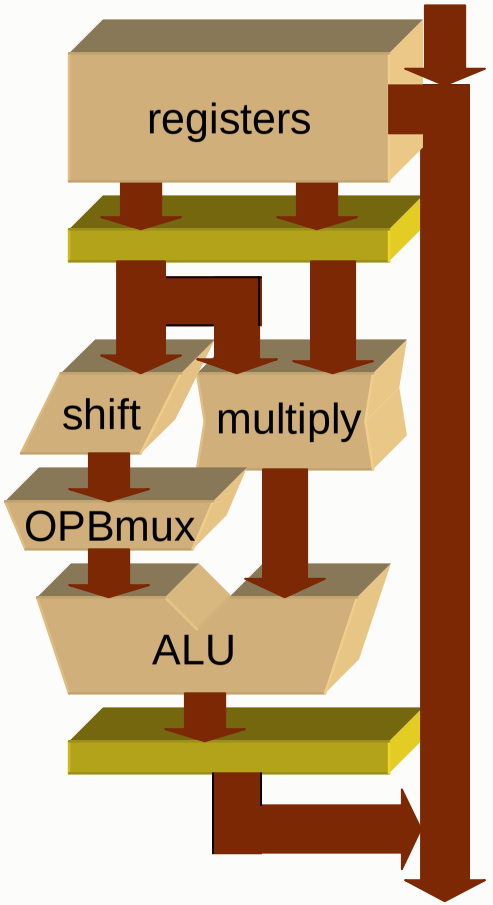
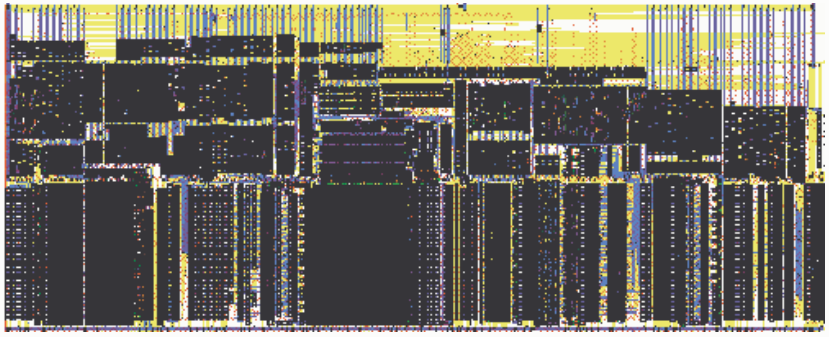


- Released 1996
- New execution pipeline
- Register forwarding
- Branch Target Cache
- 4K 64-way set associative cache

AMULET3



Source: http://www.cs.man.ac.uk/amulet/index.html

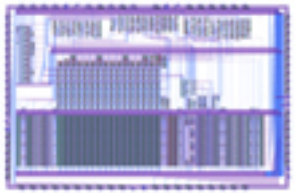
- Released in 1998
- Developed to prove commercial viability of asynchronous design
- Performance:
  - Maximum throughput: 120 MIPS
  - Power consumption: 155 mW @ 120 MIPS
  - 113000 transistors in processor core occupy 3 sq mm on .35 micron process

- Third register port added making nearly all instructions single cycle
- Reorder buffer allows out-of-order execution
- Branch predictor improved to require fewer memory cycles
- Interrupts routed to prefetch stage to handle power-saving "Halt" operations more cleanly

Comparative performance

	AMULET1	AMULET2	AMULET3	ARM710	ARM810
Process	1 μm	0.5 μm	0.35 μm	0.6μm	0.5μm
Core Area	25 mm^2	25 mm^2	21 mm^2	32 mm^2	76 mm^2
Transistors	58,374	93,000	113,000	570,295	836,022
Power	152 mW	140 mW	155 mW	120 mW	500 mW
MIPS/W	77	285	780	192	172

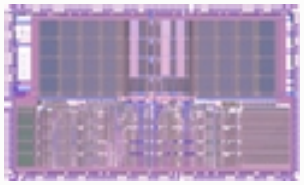
CAM – Caltech Asynchronous Microprocessor



Source: http://async.cs.caltech.edu

- The world's first asynchronous microprocessor
- Fabricated in 1989
- 16-bit RISC machine with 16 general-purpose registers
- Peak performance in HP 1.6µm CMOS
  - 5 MIPS at 2V drawing 5.2mA of current
  - 18 MIPS at 5V drawing 45mA
  - 26 MIPS at 10V drawing 105mA

miniMIPS



Source: http://async.cs.caltech.edu

- **Asynchronous MIPS R3000**
- **Designed between 1995 and 1998**
- **Peak performance in HP 0.6 µm CMOS**
  - 180 MIPS and 4W at 3.3V and 25o
  - 100 MIPS and 850mW at 2.0V and 25o
  - 60 MIPS and 220mW at 1.5V and 25o
- **Expected 280 MHz, got about 180 MHz due to:**
  - HP process
  - Layout errors

Comparative performance

	MiniMIPS @3.3V	MiniMIPS @2V	AMULET2e	StrongARM SA110
Process	0.6 μm	0.6 μm	0.5 μm	0.35 μm
Power	7 W	1 W	150 mW	120 mW
$MIPS^2/E$ 10^{21} $J^{-1}s^{-2}$	3100	3375	365	14420

- Better than Amulet2e in terms of performance per unit of energy
- Difficult to compare – different process technology, ISAs, etc.

So… Why not fully asynchronous?

- **Fully asynchronous benefits**
  - No clock, very low power
  - Average case performance may be better
- **However…**
  - Complete migration to asynchronous is not feasible immediately
  - Lack of mature CAD tools for fully asynchronous design…
  - … and inertia
- **GALS provides an intermediate solution**
  - Assumes locally clocked, fully synchronous regions
  - Globally asynchronous communication among regions

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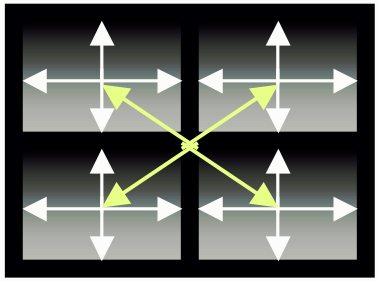
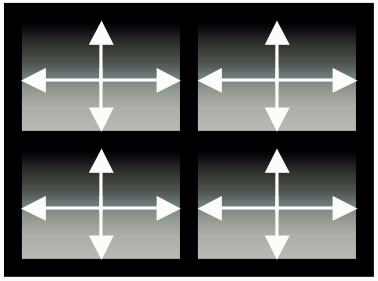
GALS systems: Why and how ?

GALS design benefits

Synchronous



GALS



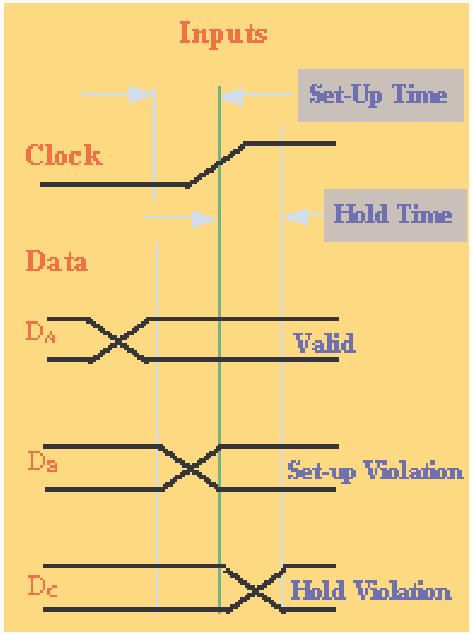
- **Lack of a global clock**
  - Less design effort and cost for dealing with clock skew
  - Less power consumption
- **Potential for fine-grain adaptability**
  - Different speeds among synchronous blocks
  - Different voltages, and hence potential for lower power consumption
  - Can be used with on-the-fly application-driven adaptation

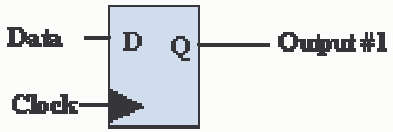
GALS design issues

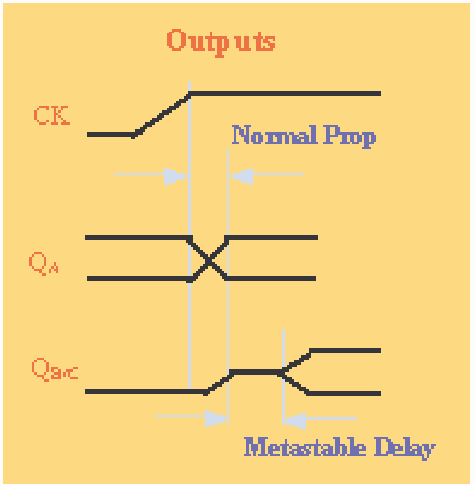
- **Metastability resolution**
  - Always a problem when interfacing clock domains
  - Synchronizers and arbiters
  - Possible solution: mixed-timing FIFOs [Chelcea and Nowick, DAC 2001, WCED 2002]
- **Local clock generation**
  - Ring oscillators [Muttersbach et al., ASYNC 2000]
- **Failure modeling**
  - Synchronization failures can happen
  - The goal is to maximize Mean Time Between Failure (MTBF)

Metastability

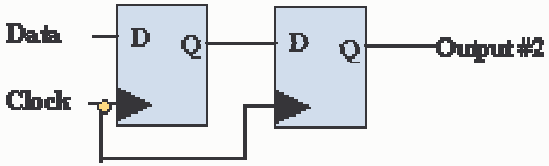
- **Asynchronous signals may violate**
  - Setup time
  - Hold time
  - Both
- **Hence the possibility of a metastable state**

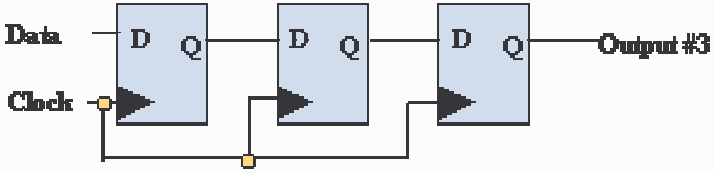




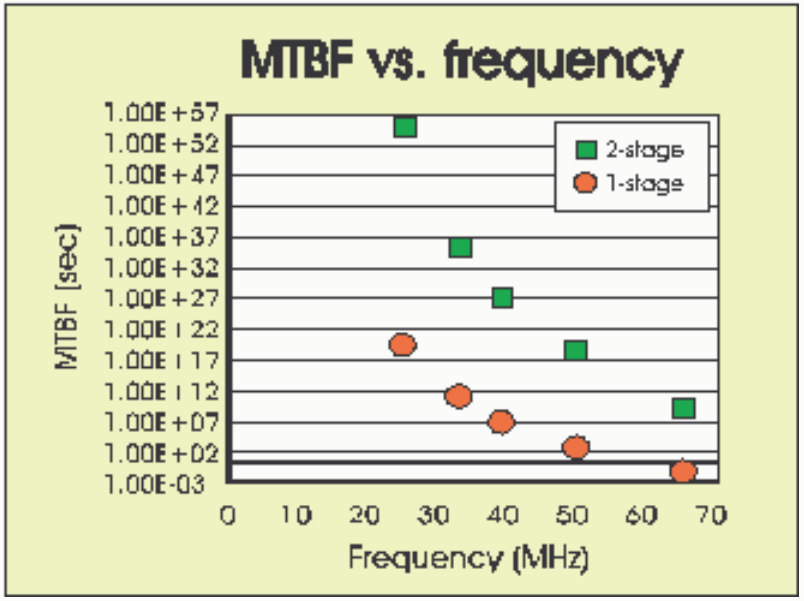


Using synchronizers





- Adding a second FF will reduce the chance of the output going metastable.
- The output from the first flip flop may go valid, before the second flip flop is clocked.
- Adding yet another FF will reduce the probability that its output will be unstable even more.



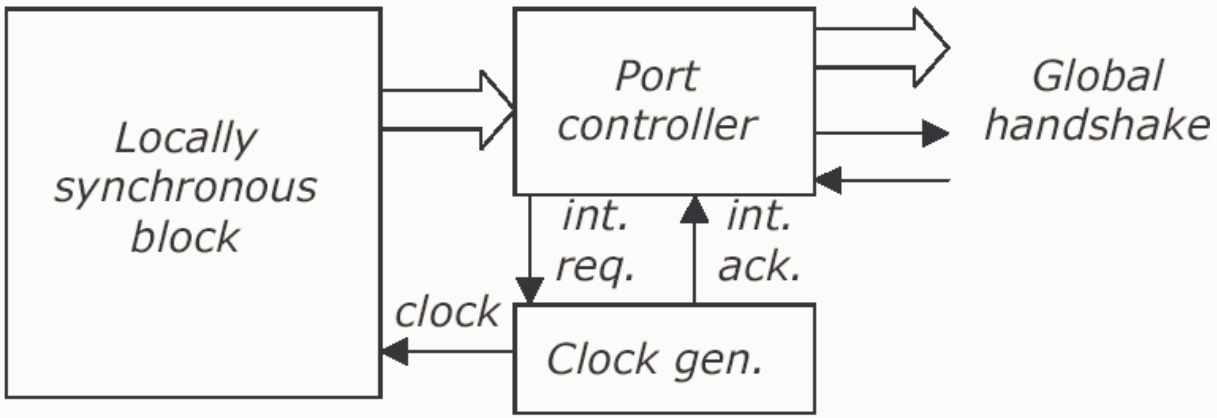
Source: Texas Instruments

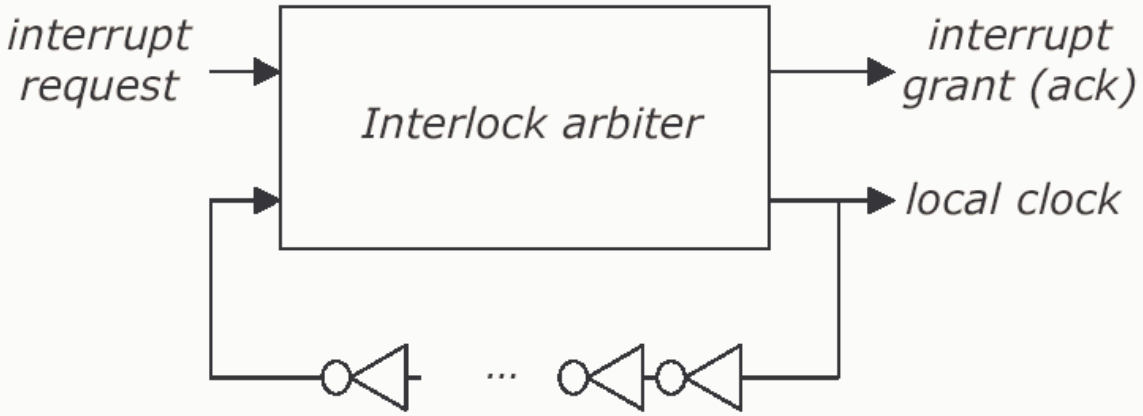
Pausible clocks

- **Some applications cannot live with a significant failure rate:**
  - Multiprocessing
  - Cryptography and security applications
  - Mission critical applications

- **Idea for accommodating metastability [Yun et al., ICCD 1996]:**
  - Pause the passive phase of a local clock, long enough to allow metastability to resolve. Then the clock can be generated by an interlock arbiter.

Pausible clocks





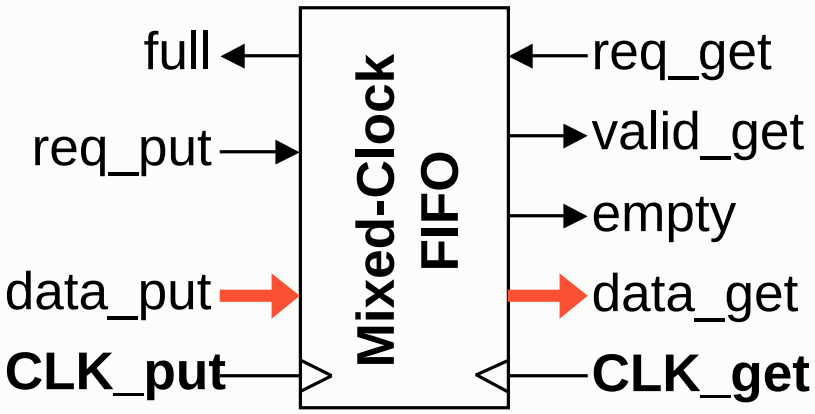
Source: Yun et al., 1996

Mixed timing FIFOs

- **Mixed timing or asynchronous FIFOs [Chelcea and Nowick, DAC 2001, WCED 2002]**
  - Low-latency
- **Modular and scalable:**
  - Define interfaces for each combination of Synchronous or Asynchronous domains
  - Combine interfaces to design new async/sync FIFO's
- **High throughput:**
  - In steady state: no synchronization overhead, no failure probability
  - Enqueue/Dequeue data items: one/cycle
- **Low area overheads**
- **Also, solve issue of long interconnect delays between domains**

Mixed-timing FIFOs

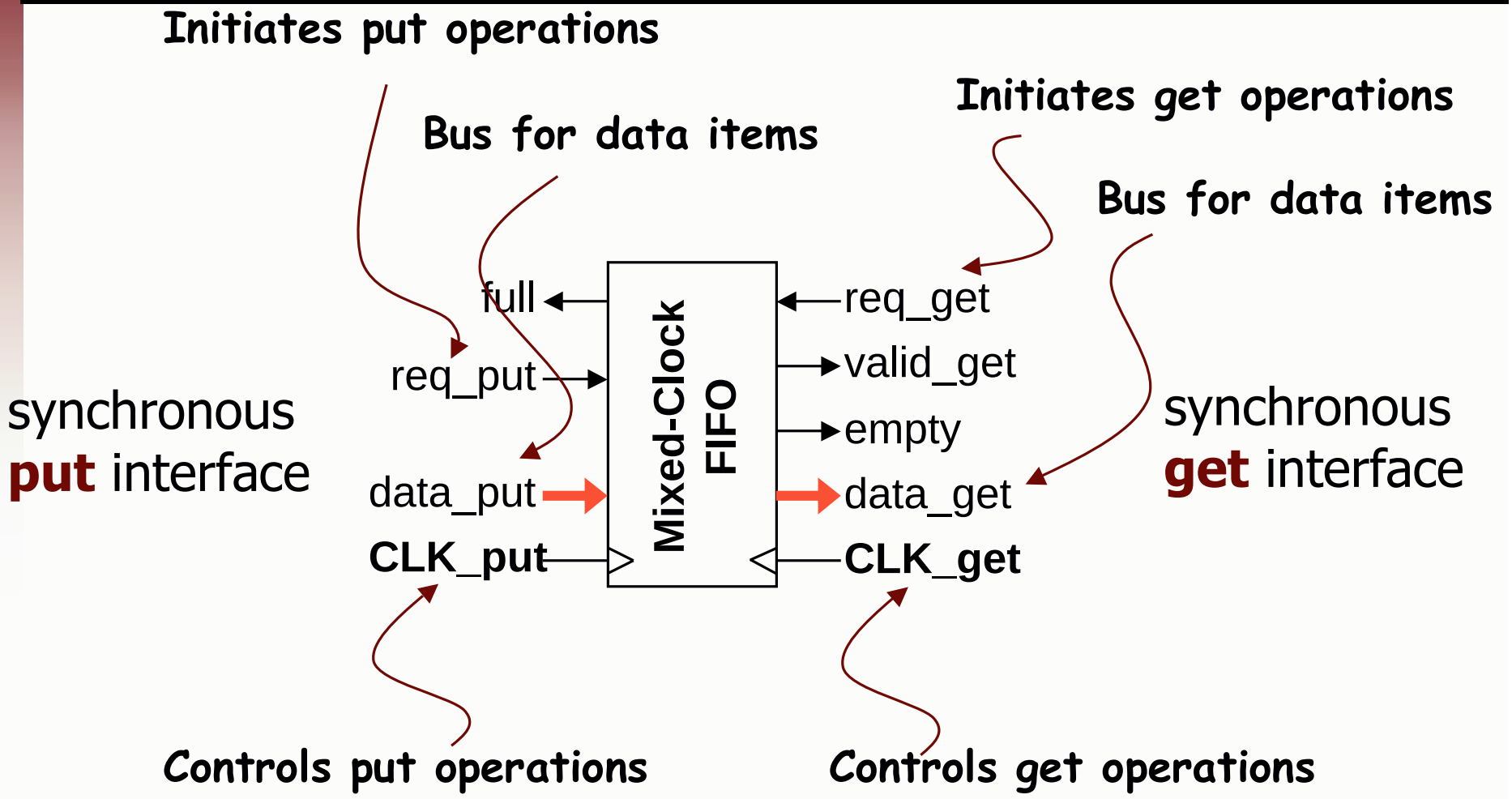
synchronous **put** interface



synchronous **get** interface

Source: Chelcea and Nowick, 2001, 2002

Mixed-timing FIFOs



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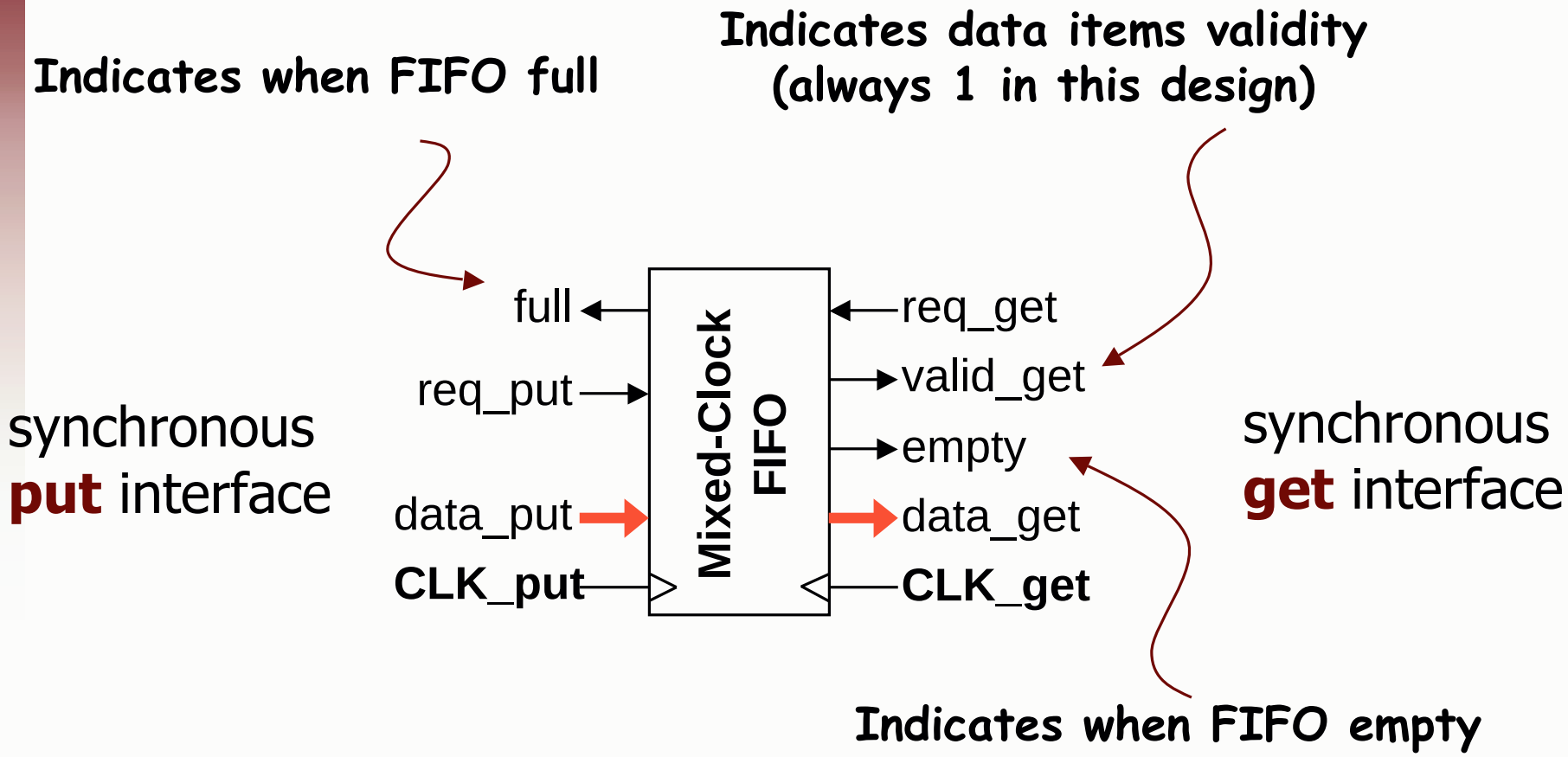

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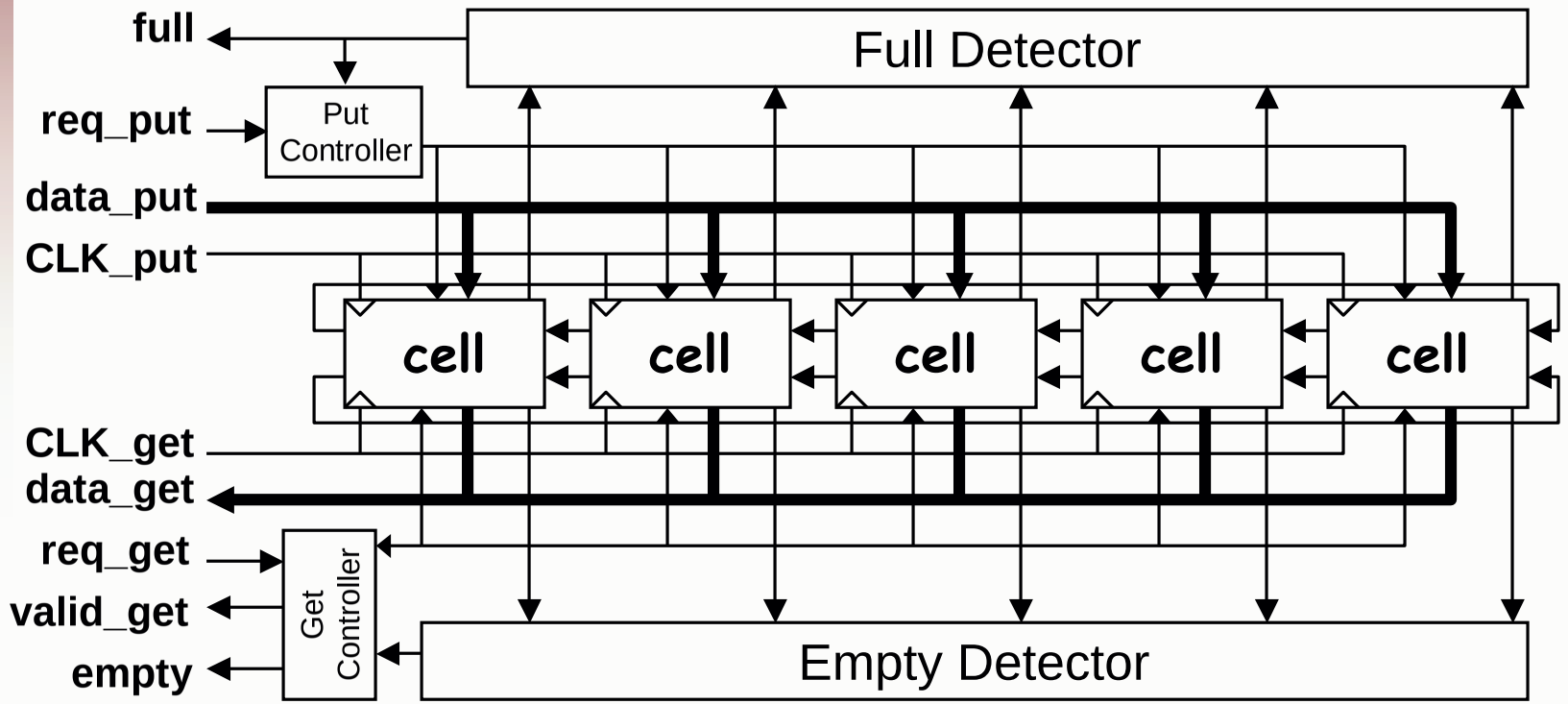

Source: Chelcea and Nowick, 2001, 2002

Local clock generation

- **Ring oscillators**
  - Pro: Simple
  - Con: Cannot be controlled externally
  - … But they can be coupled with the “local control” of speed and/or voltage
- **Local PLLs**
  - Pro: Externally controlled
  - Con: More costly
  - … but they “scale” [IWLS 2002, Focus Group on GALS]

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Power-performance evaluation of GALS processors

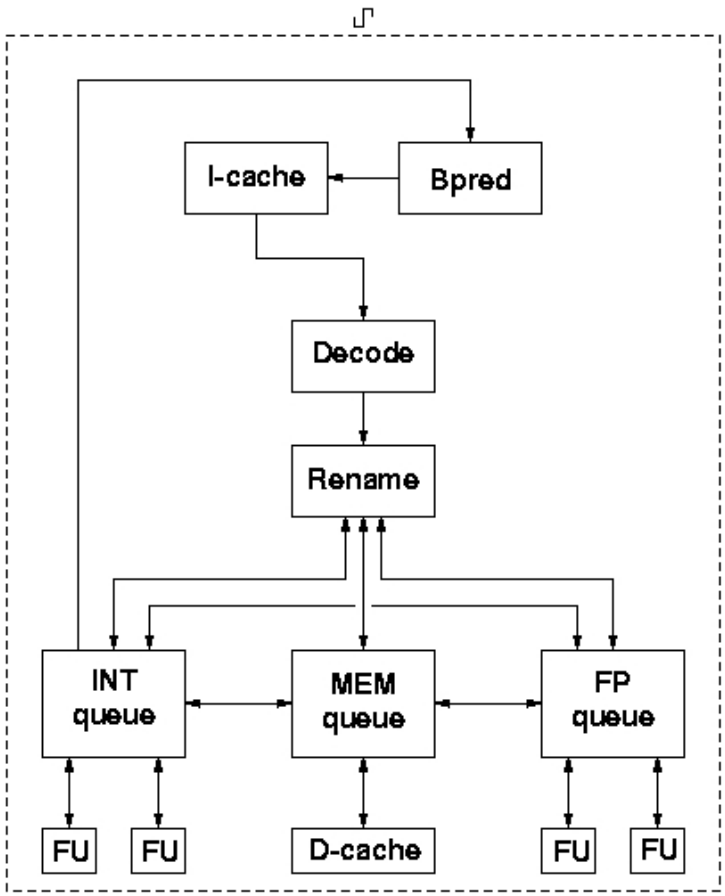
Architecture definition

- **Automatic partitioning into clock domains [Hemani et al., DAC 1999]**
  - Applied only to random logic, not helpful for high-end processors
- **A typical superscalar core exhibits "natural decoupling":**
  - Front-end (I-cache and BP hardware)
  - Decode, Register renaming
  - Integer, FP and memory "domains"
- **Local clock grids usually follow the same type of partitioning**

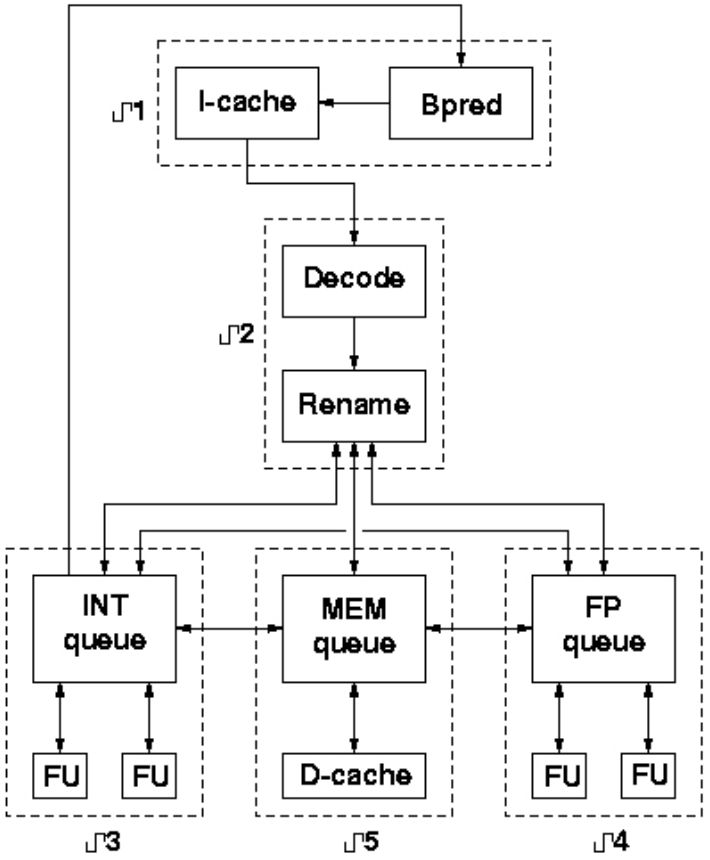
Architecture definition

- **Starting point:**
  - A hypothetical synchronous machine resembling the Alpha 21264
- **GALS architecture: satisfies physical, as well as architectural constraints**
- **Five clock domains**
  - 1. I-cache, B-pred (FETCH)
  - 2. Decode, rename (DECODE)
  - 3. Integer issue queue, integer units (INT)
  - 4. Memory issue queue, d-cache (MEM)
  - 5. Floating point issue, floating point units (FP)
- **Clock domains are interfaced using asynchronous FIFOs**

Architecture definition



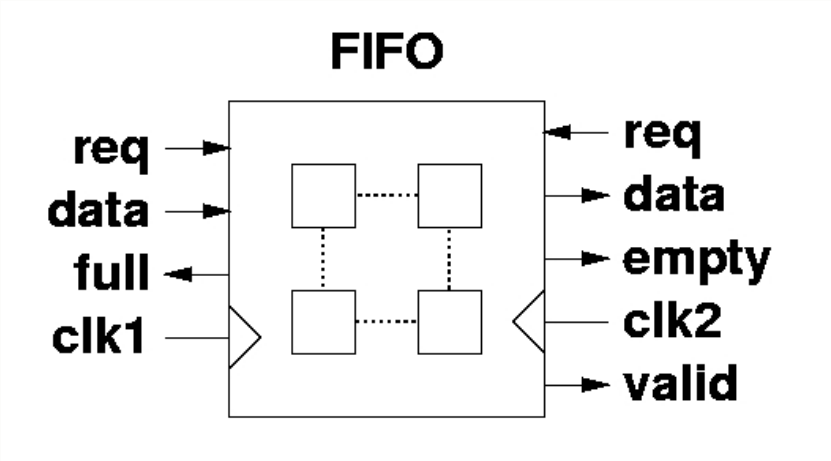
Synchronous (base) processor



GALS processor

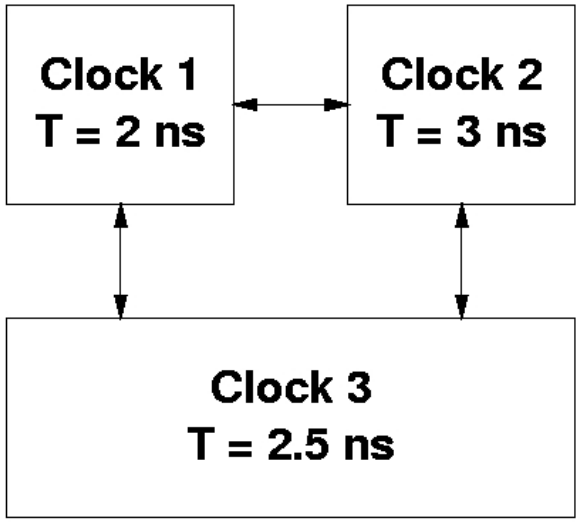
Mixed timing communication

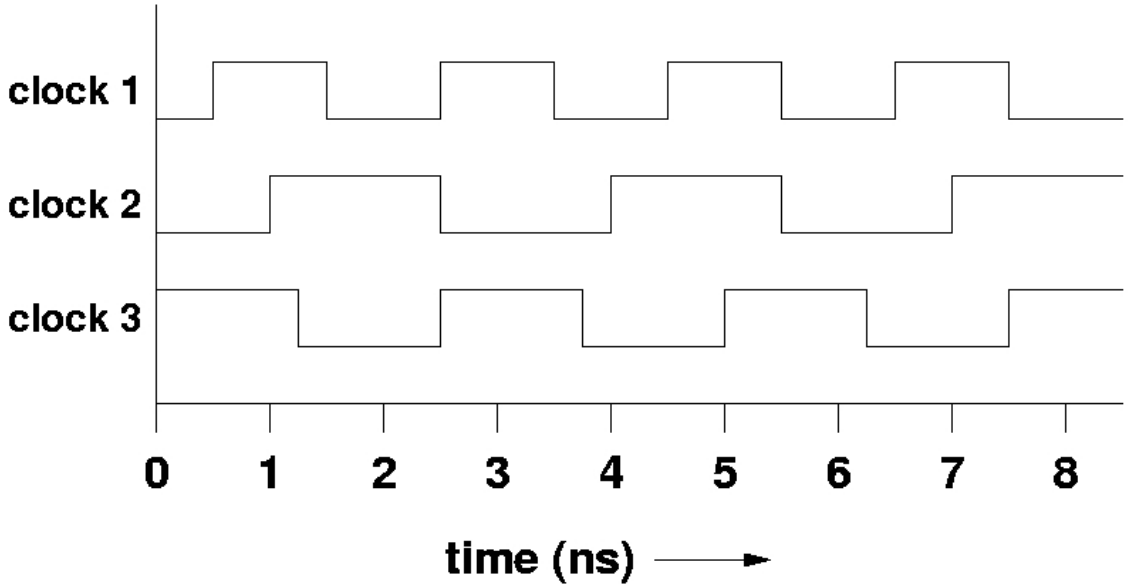
- **Used the token-ring based FIFO design**
  - [Chelcea and Nowick, DAC 2001, WCED 2002]
  - Interfaces two clocks by synchronizing control signals
  - Provides full throughput and low latency in steady state
  - Included cycle-accurate model in our simulation environment



Simulation framework

- **Event-driven simulation engine: sim-GALS**
  - Each clock domain is represented by one set of periodic events
- **Reused some of the primitives in SimpleScalar and Wattch**

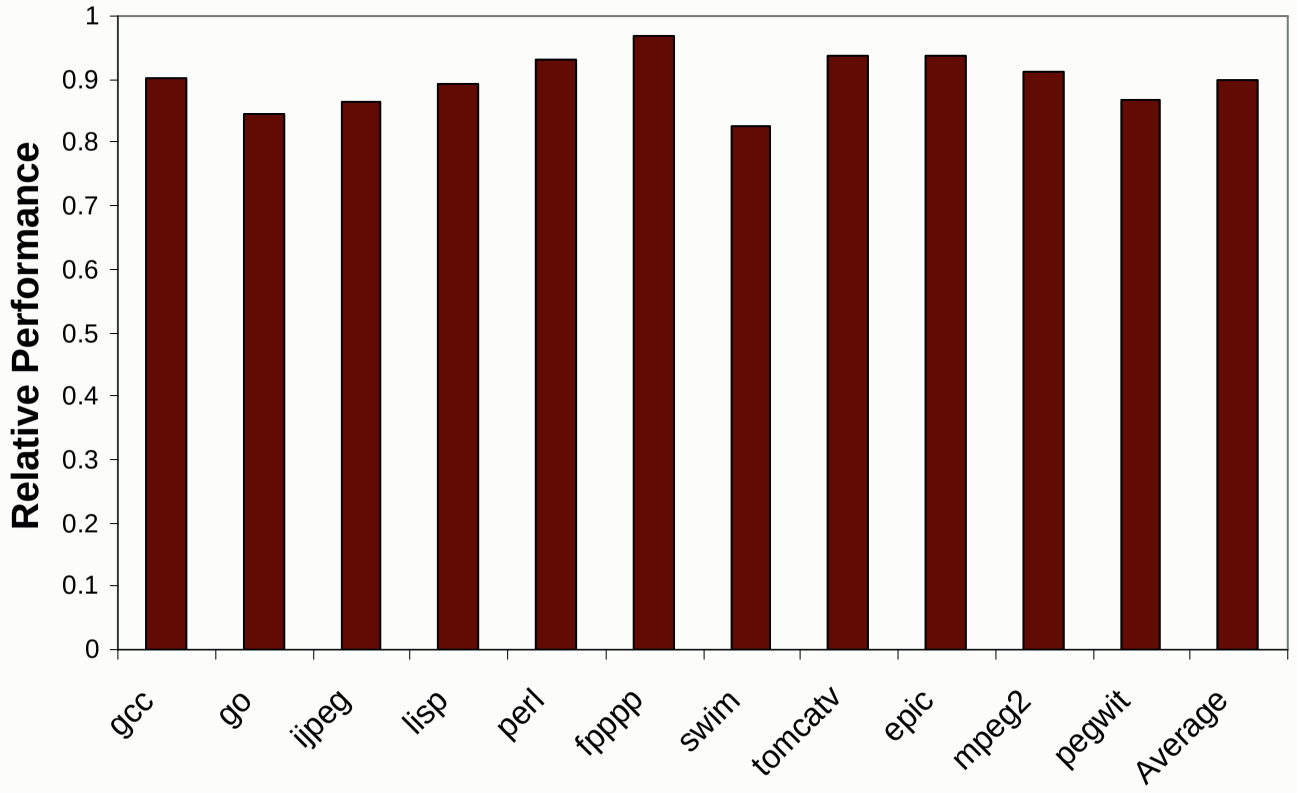




Microarchitecture settings

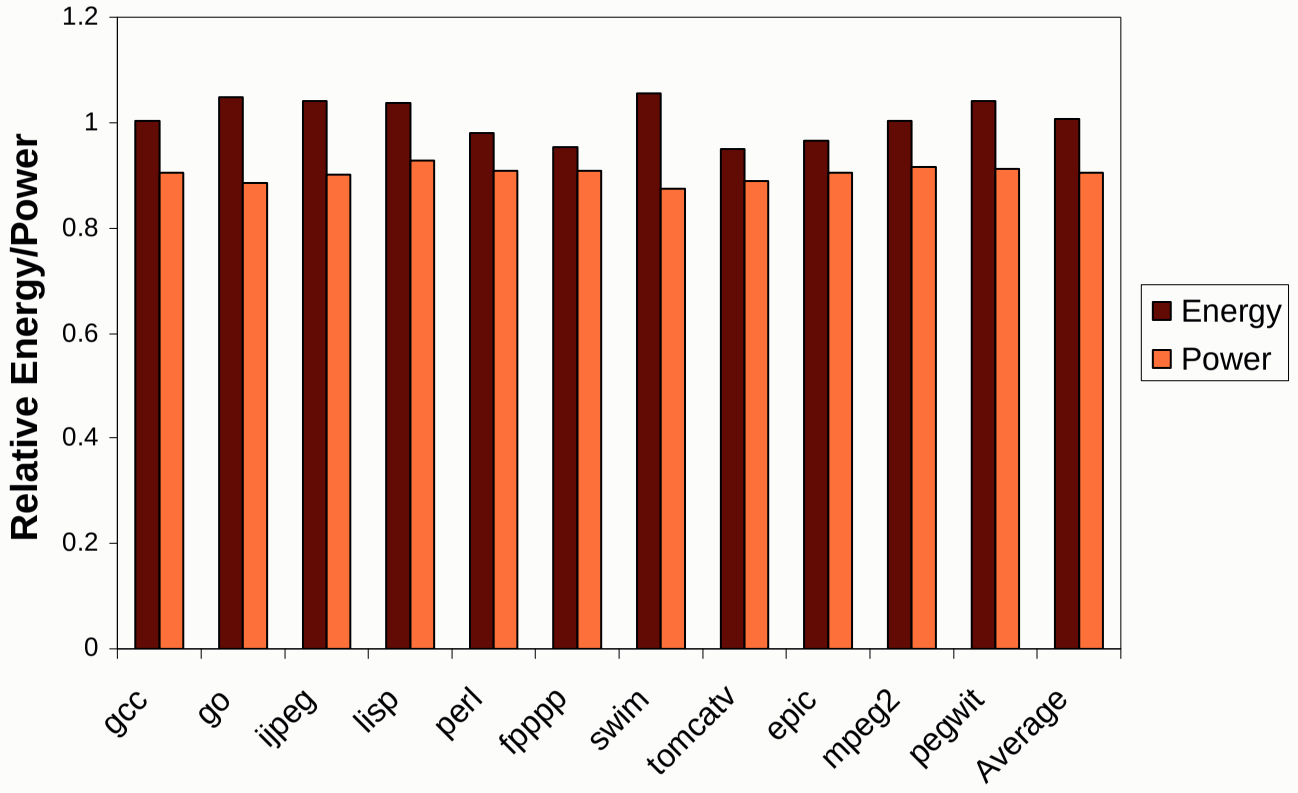
Fetch, decode, commit rate	4 inst/cycle
Integer issue queue size	20
FP issue queue size	16
Memory issue queue size	16
Integer registers	72
FP registers	72
L1 data cache	16KB 4-way 1 cycle latency
L1 instruction cache	16KB direct-mapped 1 cycle latency
L2 unified cache	256KB 4-way 6 cycles latency
ALUs	4 Int, 4 FPs
Clock gating	1-2 cycles for restarting the clock

Performance



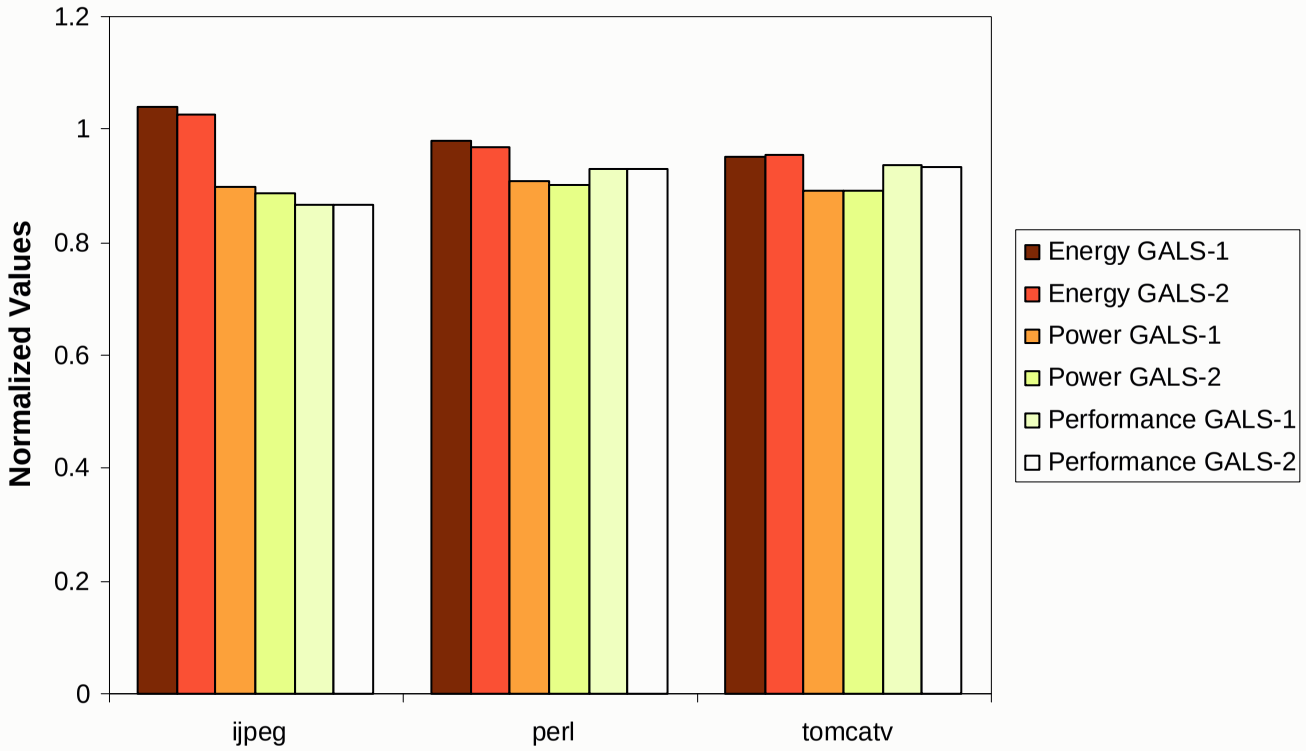
- 10% average performance penalty (3-18%)

Energy and power



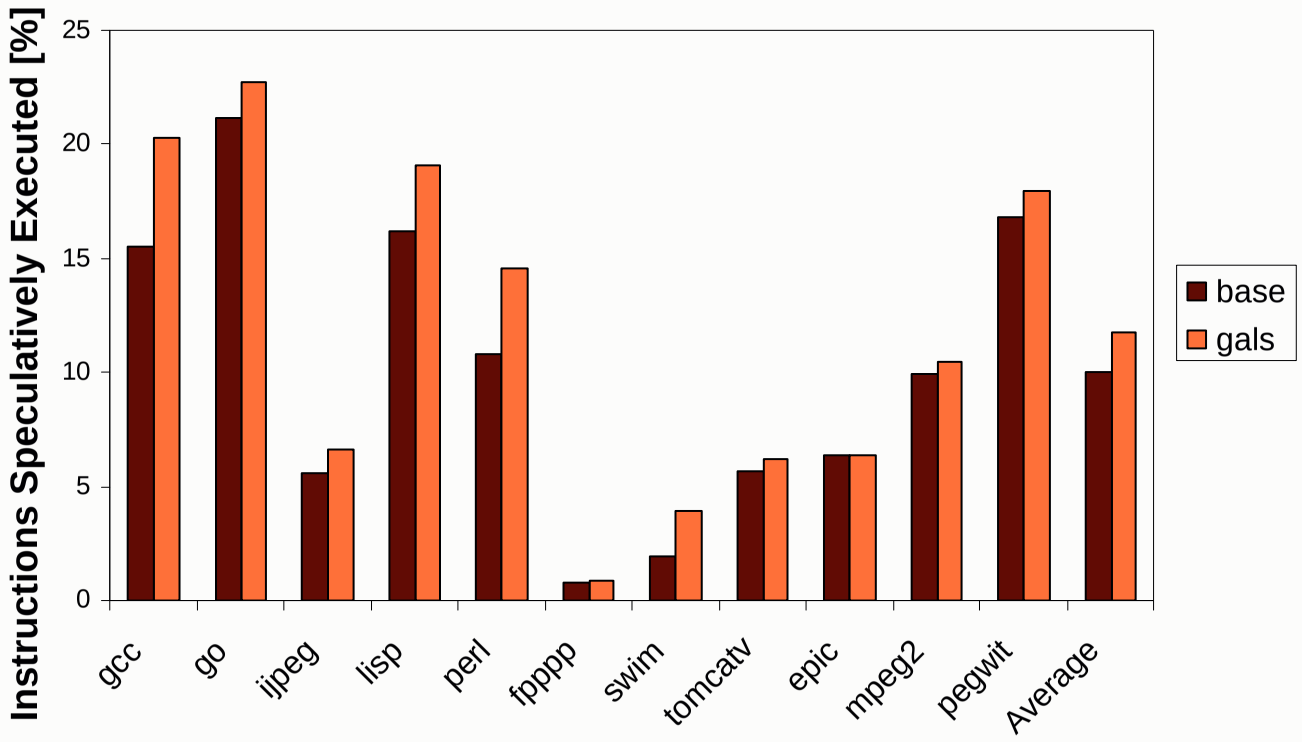
- Elimination of global clock does not necessarily reduce total energy consumption
- Average power consumption is reduced (10% on average)

Impact of clock stopping overhead



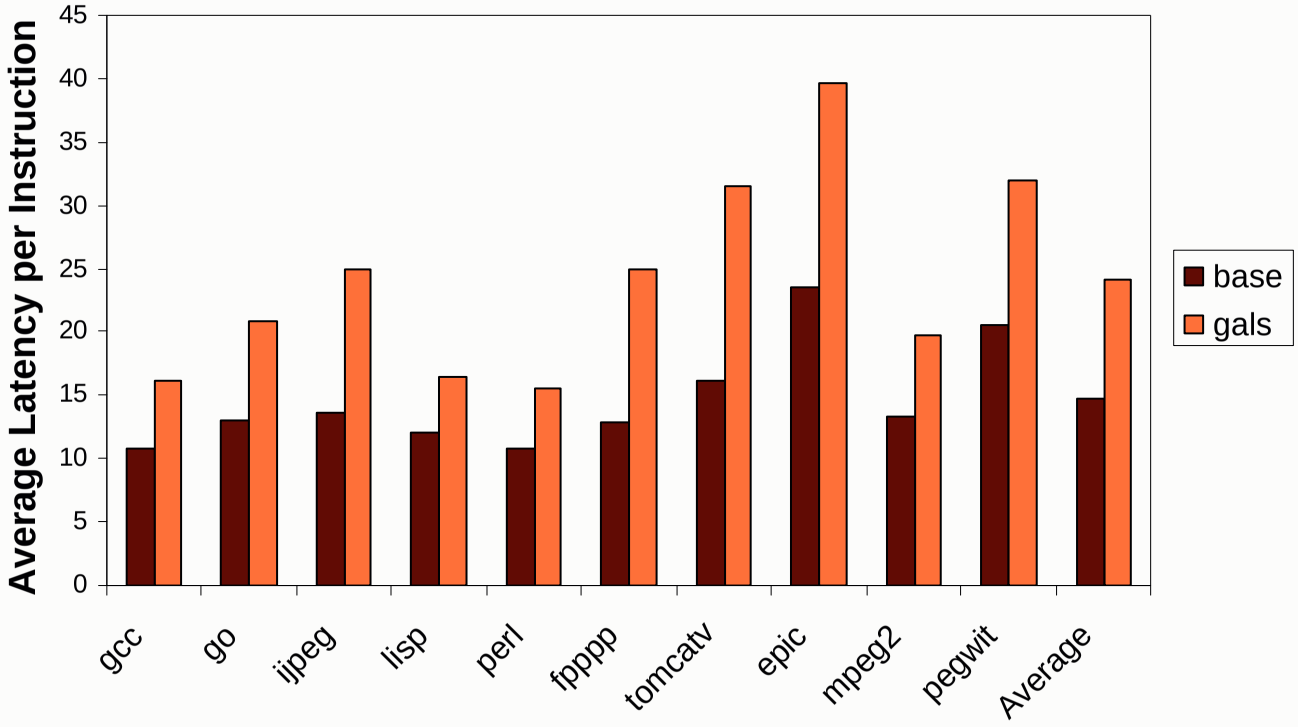
- Shutdown a clock domain after 4 idle cycles
- Restart it when decode stage detects an instruction which “needs” that domain
- Minimal impact of clock stopping/restarting overhead

Speculative execution



- On average, 2% more instructions are speculatively executed
- In the worst case, 5% more instructions are speculatively executed

Average latency per instruction

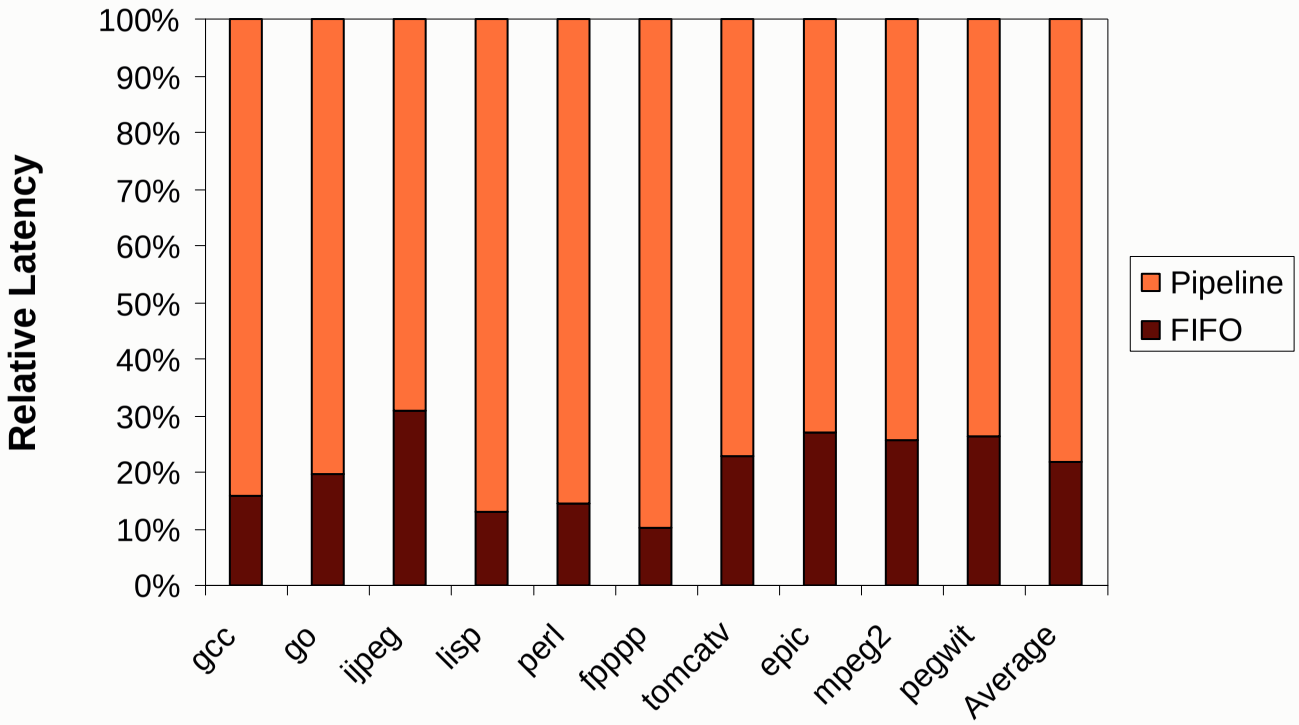


- End-to-end latency increases from 15 to 24 cycles, on average

Energy and performance trends

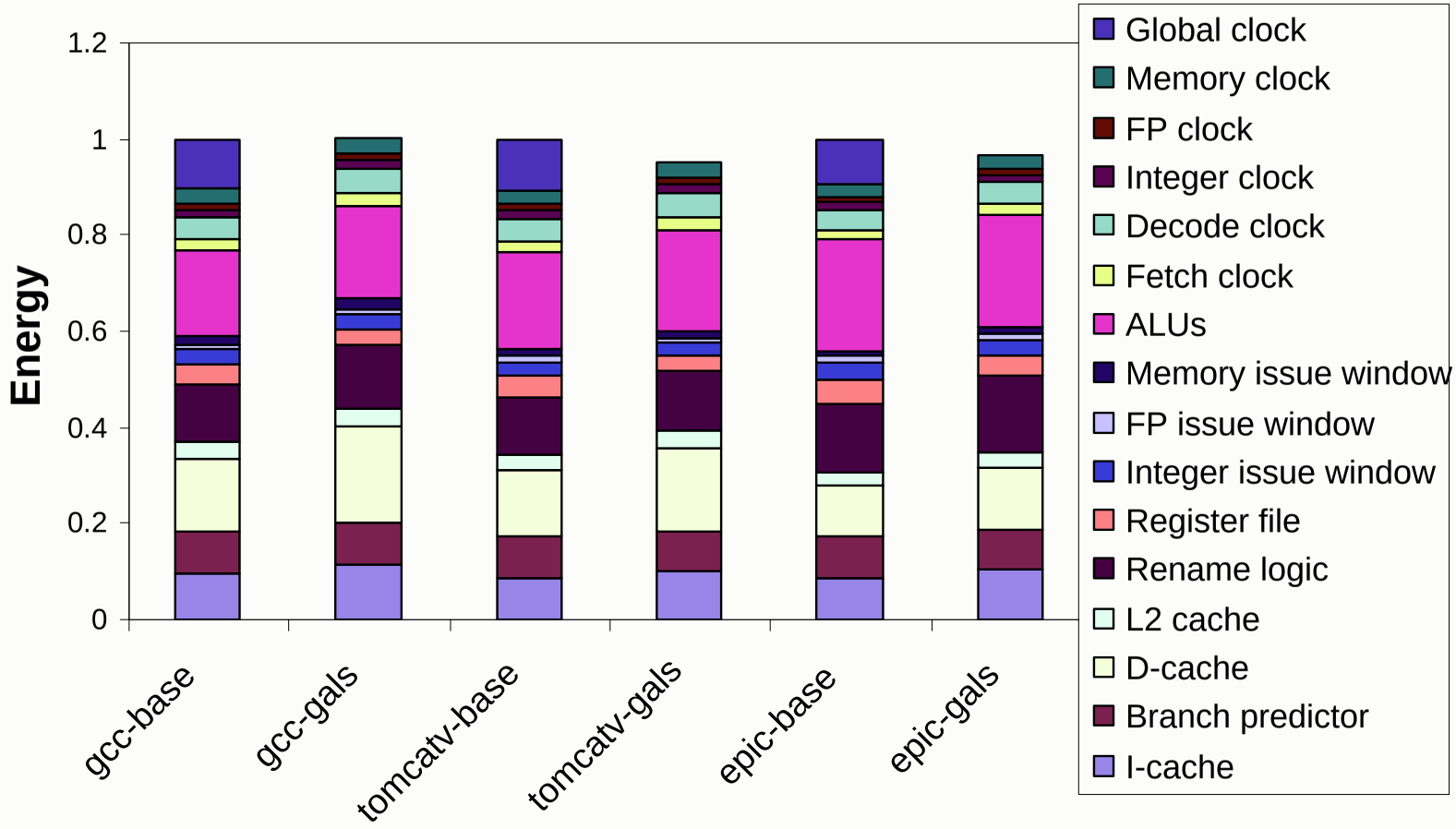
- **Average power decreases, but overall energy may increase**
- **Reasons:**
  - Performance drops due to asynchronous communication
    - Hence longer execution time and more overhead for unused modules
  - Longer branch recovery pipeline
    - Consequently, more speculative execution
  - Higher fetch to commit time for each instruction
  - Higher occupancies of rename tables and issue queues

Where does performance go?



- Asynchronous FIFOs introduce 22% latency overhead on average
- The rest of latency is spent in other stages of the pipeline

Where does energy go?



- **Longer execution times translate into larger energy costs**

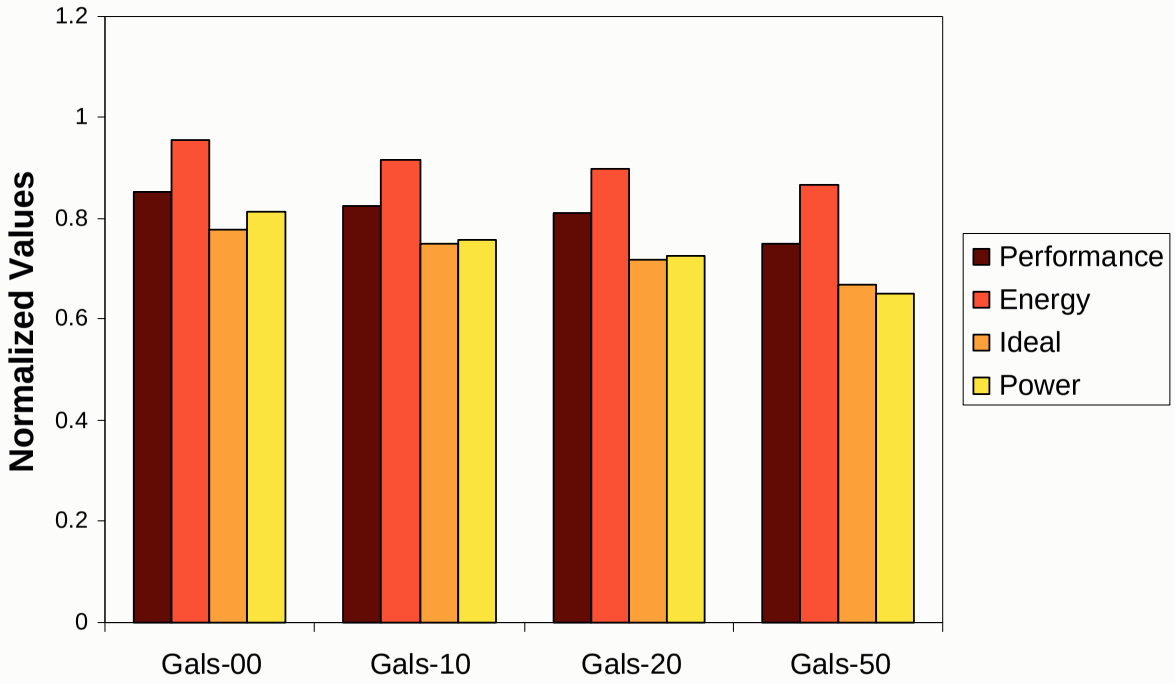
Delay - voltage dependency

- **Fine-grain voltage reduction can be beneficial in GALS systems**
  - Each clock domain can be run at a different speed

$$D \propto \frac{V_{dd}}{(V_{dd} - V_t)^{\alpha}}$$

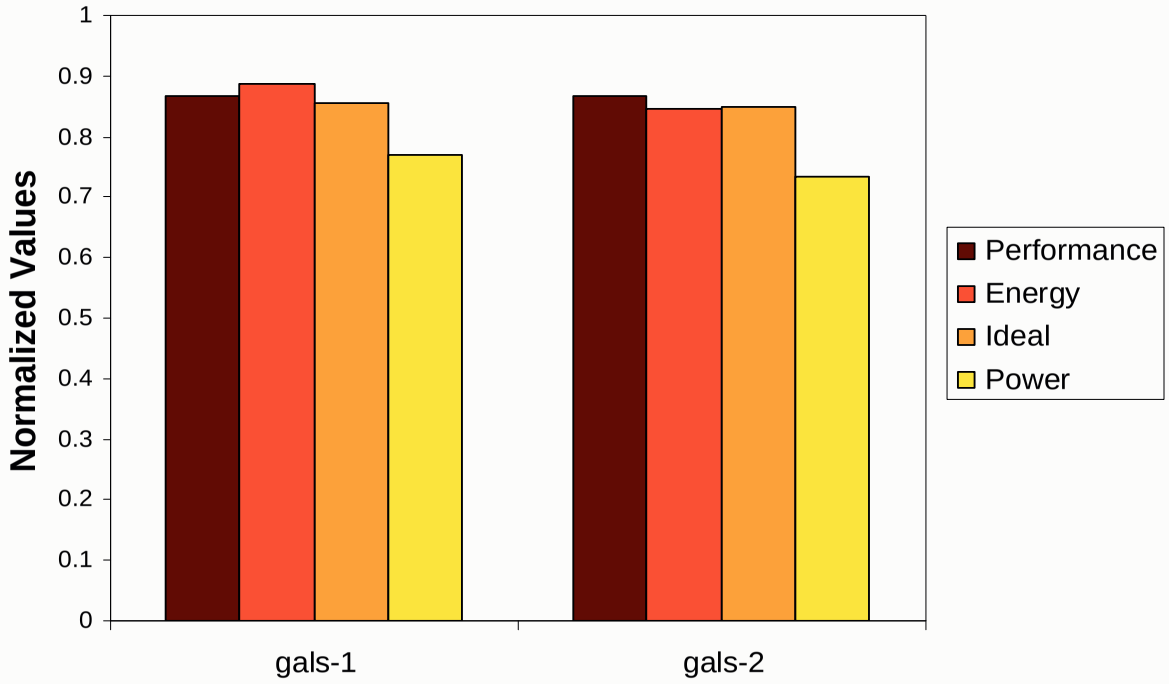
  - V_{dd} is the supply voltage
  - V_t is the threshold voltage
  - α is a technology-defined constant between 1 and 2;
  - α is 1.2-1.6 for present generation [Chen et al, JSSC 1998]

Selective voltage reduction for ijpeg



- **GALS version gives some energy savings**
  - Fetch clock slowed down 10%
  - FP clock slowed down 20%
  - Memory clock slowed down 0-10-20-50%
  - Ideal: base, fully synchronous version with reduced voltage

Selective voltage reduction for gcc



- 1: FP clock: 1.5; 2: FP clock: 3.0
- GALS version is as good as the fully synchronous baseline

Related reading list

- D. M. Chapiro, Globally Asynchronous Locally Synchronous Systems. PhD thesis, Stanford University, 1984.
- Ivan E. Sutherland. Micropipelines. (Turing award lecture) Communications of the ACM, 32(6):720-738, June 1989.
- Robert F. Sproull, Ivan E. Sutherland, and Charles E. Molnar. The counterflow pipeline processor architecture. IEEE Design & Test of Computers, 11(3):48-59, Fall 1994.
- K.Y. Yun, R.P. Donohue. Pausible Clocking: A First Step Toward Heterogeneous Systems. Computer Design: In Proc. Intl. Conference on VLSI in Computers and Processors (ICCD), 1996, pages: 118-123.
- A. Hemani, T. Meincke, S. Kumar, A. Postula, T. Olsson, P. Nilsson, J. Oberg, P. Ellervee, and D. Lundqvist. Lower Power Consumption in Clock By Using Globally Asynchronous Locally Synchronous Design Style. In Proc. Design Automation Conference (DAC), 1999.
- J. Muttersbach, T. Villiger, and W. Fitchner. Practical Design of Globally Asynchronous Locally Synchronous Systems. In Proc. Intl. Symposium on Advanced Research in Asynchronous Circuits and Systems (ASYNC), 2000.
- I.E. Sutherland, S. Fairbanks. GasP - A Minimal FIFO Control. In Proc. Intl. Symposium on Advanced Research in Asynchronous Circuits and Systems (ASYNC), 2001.
- T. Chelcea and S. M. Nowick. Robust Interfaces for Mixed-Timing Systems with Application to Latency-Insensitive Protocols. In Proc. Design Automation Conference (DAC), 2001.
- A. Iyer and D. Marculescu. Power and Performance Evaluation of Globally Asynchronous, Locally Synchronous Processors. In Proc. Intl. Symposium on Computer Architecture (ISCA), 2002, pages: 158-168.
- http://www.cs.man.ac.uk/amulet/index.html
- http://www.async.caltech.edu/

Schedule

- 8:30-9:30 (Diana Marculescu)
  - Trends and issues in clock distribution
  - How much asynchrony do we want?
  - Motivation for GALS, synchronization issues, deadlock prevention, possible inter-clocking domain communication schemes
  - GALS processors: power/performance evaluation
- 9:30-9:45 Break
- 9:45-10:45 (Dave Albonesi)
  - GALS processors: power/performance evaluation (cont'd)
  - Workload characterization and impact on the use of fine grain speed/voltage scaling
- 10:45-11:00 Break
- 11:00-12:00 (Pradip Bose)
  - Case study - LPX, an IPCMOS based processor
- 12:00-12:20 (Diana Marculescu)
  - Looking in the crystal ball: Where will GALS be used?
  - Concluding remarks
- 12:20-12:30 Q&A