REVERSIBLE COMPUTING

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INTRODUCTION

Physics and Thermodynamics

Theory of Reversible Computation

Reversible Gates
- Ballistic
- Brownian
- SCRL

Reversible Architectures
- Pendulum
- Flattop
- Optimally Scalable Computer Architecture?

Physics for Architects

***Irreversible* Logic v. *Reversible* Physics**

- Physical implementations of logic?
- How is reversibility lost?
- Is it worth reclaiming?

Dissipation → Waste Power → Heat

Zero Power Dissipation is Approachable (!)

THE 411 ON DISSIPATION

Dissipation Associated with Irreversibility

- Why does irreversibility cause dissipation?
- Loss of Information: 2 bits ➔ 1 bit
- Generates Entropy (Landauer's Principle)

$$\Delta \mathrm{S} = k_B ln 2 \text{ per bit}$$

Dissipation Associated with Switching

- Charge Sharing, Un-Driven Signals
- SCRL, Quasi-static Operation

gniruT Machines

Do we sacrifice *universality* for *reversibility*?

Short answer: No, but...

- No such single input/output gates...
- No such double input/output gates...
- Many such triple input/output gates! (Toffoli, Fredkin, *etc.*)

Reversibility requires more wires.

GOING BALLISTIC

Inspired by Classical Mechanics (18.01)

- Ideal Hard Spheres!
- Ideal Flat Planes!

Computes in finite time with <u>zero</u> energy!

- ...also a perpetual motion machine
- small deviations from ideal are inevitable
- deviations from ideal require correction (grooves in planes, *etc.)*

Brownian Notion

Let probability do the work

- Run forwards and backwards
- Small drift velocity

Some Biological Systems

- Enzymes catalyze reactions both ways
- Driven by eliminating a product

Brownian Turing Machine

SCRL

Split-Phase...
- Swinging Power Rails act as clocks
- Transistors switch only when
  Power = Ground, avoiding dissipation

...Charge Recovery
- Inputs/Outputs always driven
- Inverse "Keeper" function blocks
- Blocks segregated by transmission gates
- Pipeline-able

Pendulum (the Good)

Reasonably Space Efficient

- Implements R2000-*esque* ISA
- R2000: ~185,000 transistors (CMOS)
- Pendulum: ~200,000 transistors (SCRL)
- ~17% of pins for power/ground

Bottom Line: It works.

PENDULUM (THE BAD)

No design tools available for SCRL

- Laid out by hand (~2 man years)
- But this is a solvable problem, made easier by the inherent symmetries of SCRL

No development tools available

- Reversibility protection too big/complex for hardware (reversible branches?)
- Difficulty passed to programmer/compiler
- "Garbage Stack" smacks of pure evil
- Wires...

FLATTOP

`Halt():` *ball[8]* → *pocket[corner]*

Billiard Ball Model Cellular Automata

- Mechanically-Inspired system
- Implemented in Silicon (3-phase SCRL)
- Scalable 2D Mesh

How Useful is it?

- Proof of Concept
- Really Hard to Analyze (lack of tools)
- Really Hard to Initialize (BBMCA is odd)

COMPUTRONIUM

...a universal digital computing substrate!

What about incommensurate scaling?

- Generates heat by volume (N^3)
- Dissipates heat by surface area (N^2)
- Must throttle back processors due to heat

Reversible computers bypass this constraint (somewhat)

- Irreversible: O(N) time per operation
- Reversible: $O(N^{1/2})$ time per operation

What's Wrong?

Asymptotically better

- Only true for big computers
- Potentially large constant factors hidden

Assumes Entropy removal is the limit

- Benefit shrinks from $\Theta(N^{1/2})$ to $\Theta(N^{1/12})$
- Computer with the mass of Saturn

But eventually this will be the case

- We want/need compact computers
- Speed of Light is a hard limit
- Still need lots of wires

THE FUTURE

Already see the benefits

- 3 orders of magnitude in Flattop
- Simulates Reality very well

Where you will see Reversible Machines:

- Large, Scalable machines (not the desktop)
- Cool, Power-efficient
- Quantum Computers

Challenges:

- Better development tools (both hard/soft)
- Where to put these wires?
- Swinging Power Supply