Molecular Mechanical Computing

Institute for Molecular Manufacturing
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Mechanical Computing Systems Using Only Links and Rotary Joints
Ralph C. Merkle, Robert A. Freitas Jr., Tad Hogg, Thomas E. Moore, Matthew S. Moses, and James Ryley
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Evaluating the friction of rotary joints in molecular machines
Tad Hogg, Matthew S. Moses and Damian G. Allis
Molecular Systems Design & Engineering, 2017, 2, 235-252
https://doi.org/10.1039/C7ME00021A
Conclusion:

$10^{21}$ FLOPS
In a sugar cube
Using 1 watt of power
With a 100 MHz clock (10 ns)

Key concept: 4-phase two rail mechanical reversible shift register
Microprocessor Clock Speeds

Cooling costs are limiting clock speeds
The Problem: $I^2R$
Typical nanoscale contacts are $\sim 13k\Omega^*$

One electron moving 10 nm in 10 ns dissipates $\sim 3 \times 10^{-18}$ J or $\sim 750$ times $kT$

*See the Landauer Formula, https://en.wikipedia.org/wiki/Landauer_formula. Although resistive losses can be avoided by adiabatic switching this raises other issues; see, for example, Helical Logic (http://www.zyvex.com/nanotech/helicalIntro.html).
Are there alternatives to electronics?
Mechanical Computing

www.imm.org/Reports/rep046.pdf
But!

Snapping, sliding, dragging, squeezing, forcing, pounding, smashing, ringing, tensioning, etc. etc. etc.
Rotary Joints + Links (10 to 20 nm) + Clocks

Periodic 1 Piconewton Forces
System Rules

• The periodic clocking forces are ~1 piconewton.
• Links make contact only through rotary joints.
• There are no unconstrained degrees of freedom.
• The system is driven by a four-phase clock.
• The system is fully reversible.
Additional Perspectives

• The time, $t$, uniquely determines the position of every link in the system, up to the uncertainty caused by thermal noise.
• The system can operate as slowly as might be desired.
• The system can operate both forwards and in reverse.
How do we compute under these constraints?
We will define two primitives:

1) A lock

2) A balance

We will then use these two primitives, along with the periodic clocking forces, to implement a shift register.
A data link can be in one of two positions. One of these positions is 0, the other is 1.
Mobile linkage

Non-mobile linkage
A lock in the (0,0) position
A lock in the (1,0) position
A lock in the (0,0) position

Top 4-Bar Linkage

Bottom 4-Bar Linkage

Connecting Link

A lock in the (1,0) position

Top 4-Bar Linkage

Connecting Link

Bottom 4-Bar Linkage

A lock in the (0,1) position

Top 4-Bar Linkage

Connecting Link

Bottom 4-Bar Linkage
Balance
A balance
A balance connected to two locks
Shift register cell with input (1,0) after clock actuation
Fredkin Gate
(logically complete)

A = 0
B
C

A = 0

B
C

A = 1
B
C

A = 1

B
C

B

C
Mechanical Clocked Fredkin Gate
(from December 2015 patent filing*)

*Mechanical Computing Systems,

WWW.IMM.ORG
What’s the energy dissipation?

1) Rotary joints have very little drag
2) Other dissipative mechanisms can have less drag
Rotary Drag Power Equation

\[ P_{rd} = K_{rd} \nu_r^2 \]

where:
- \( P_{rd} \) is the power dissipated (in watts) by rotary drag
- \( K_{rd} \) is the applicable rotary drag coefficient (in J·s or kg m\(^2\)/s)
- \( \nu_r \) is the rotational speed (in radians/second) between the housing and the rotor
housing

pyramid

rotary joint

rotor

rotary joint

{111} surfaces

{110} surface

stem

{111} surfaces

{110} surface
$K_{rd} \sim 2 \times 10^{-35} \text{ J s}$

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What’s the energy dissipation?

1) Count the rotary joints
2) Determine their rotational speed
3) Apply the equation $P_{rd} = K_{rd} \nu_r^2$
4) Neglect other dissipative mechanisms
Dissipative Mechanisms Considered

- Sliding drag (none)
- “Snap to” (none)
- EM radiation (none)
- Resistive losses (none)
- Resonance mechanisms (very small)
- Acoustic radiation (very small)
- Acoustic radiation (extremely small when canceled)
- Entropic losses (extremely small)
- Heat flows caused by stress/strain (extremely small)
- Thermal equilibration times (under 1 ps)
$10^{21}$ FLOPS* per watt in a Sugar Cube

- More efficient gate implementations
- More efficient implementations of floating point operations
- $10^{21}$ FLOPS per watt seems achievable

END OF TALK