Molecular Mechanical Computing

Institute for Molecular Manufacturing

Ralph C. Merkle, Robert A. Freitas Jr., Tad Hogg, Thomas E. Moore, Matthew S. Moses, James Ryley and Damian Allis

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

Journal of Mechanisms and Robotics, Dec 2018, 10(6): 061006

https://doi.org/10.1115/1.4041209

Evaluating the friction of rotary joints in molecular machines

Tad Hogg, Matthew S. Moses and Damian G. Allis

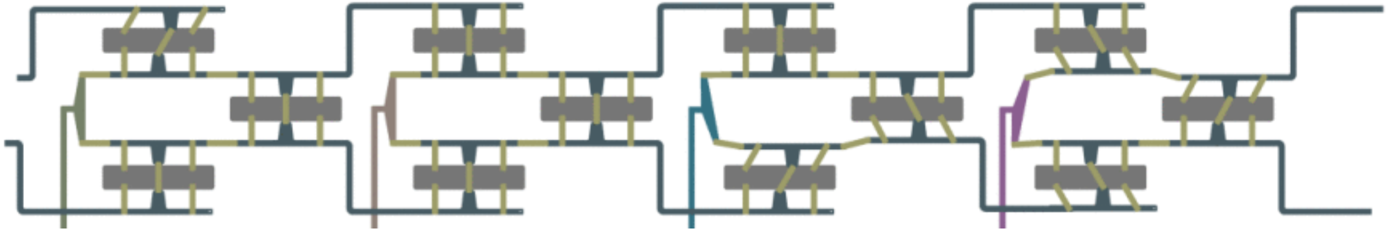
Molecular Systems Design & Engineering, 2017, 2, 235-252

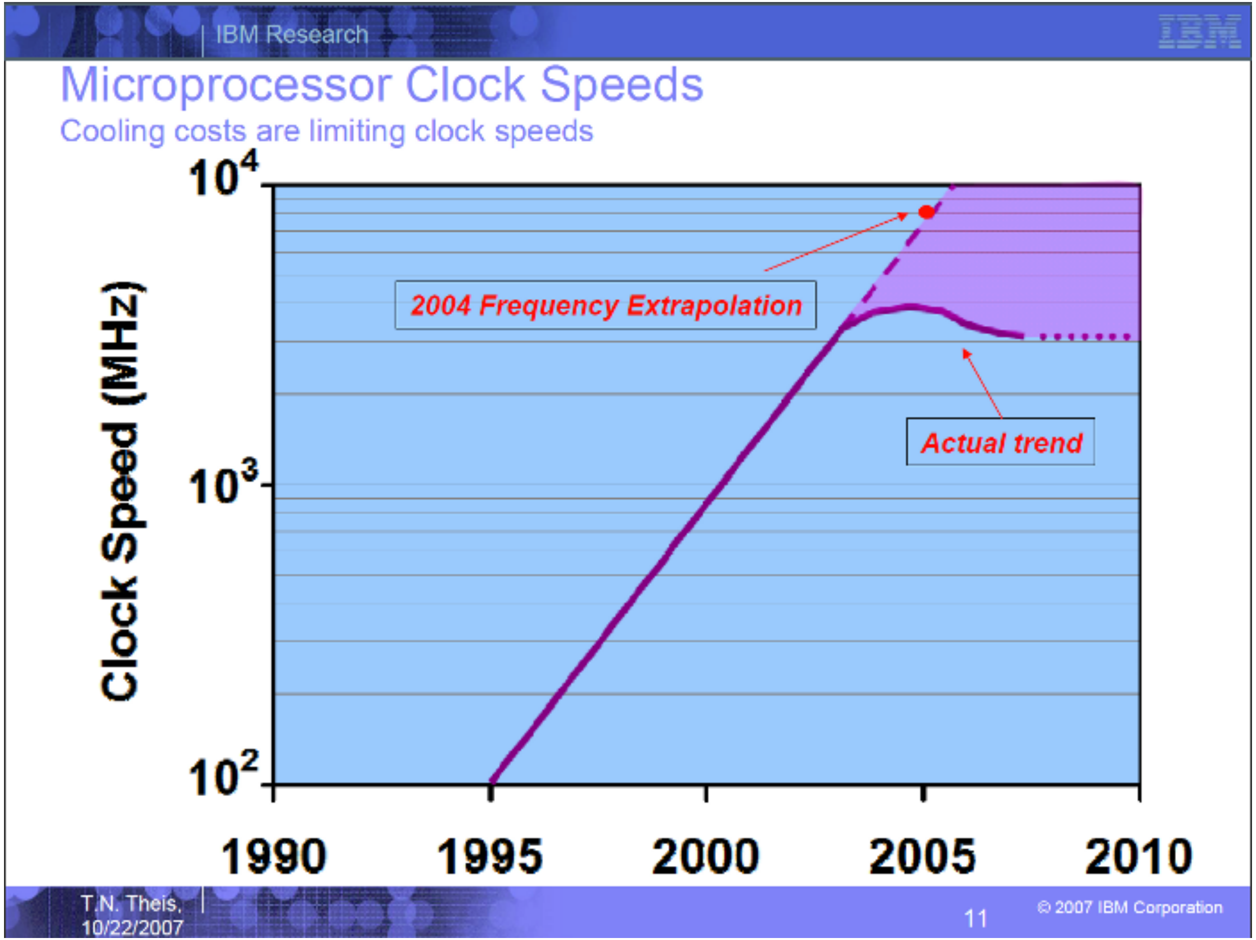
https://doi.org/10.1039/C7ME00021A

Conclusion:

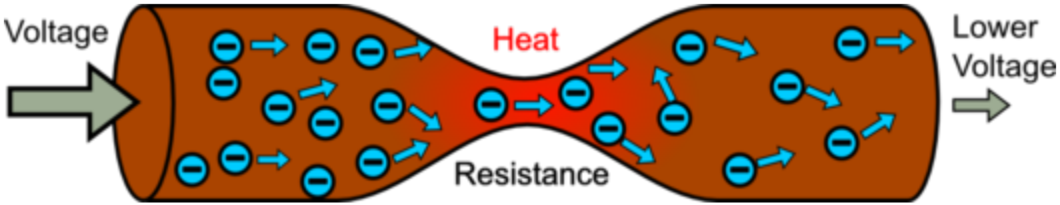
10^{21} FLOPS
In a sugar cube
Using 1 watt of power
With a 100 MHz clock (10 ns)

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

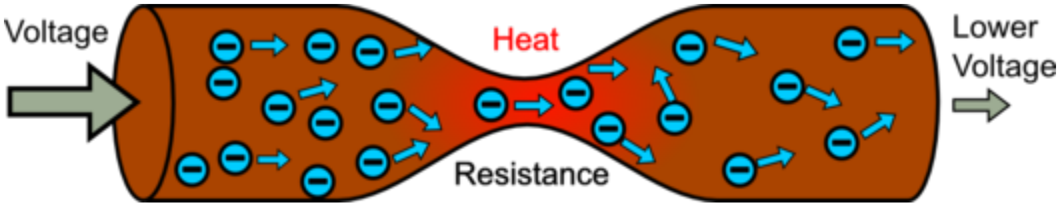



IBM Research
IBM
Microprocessor Clock Speeds
Cooling costs are limiting clock speeds
Clock Speed (MHz)
10^4
10^3
10^2
2004 Frequency Extrapolation
Actual trend
1990
1995
2000
2005
2010
T.N. Theis,
10/22/2007
11
© 2007 IBM Corporation

The Problem: I^2R



Typical nanoscale contacts are ~13kΩ*
One electron moving 10 nm in 10 ns dissipates
~3 x 10^{-18} J or ~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).

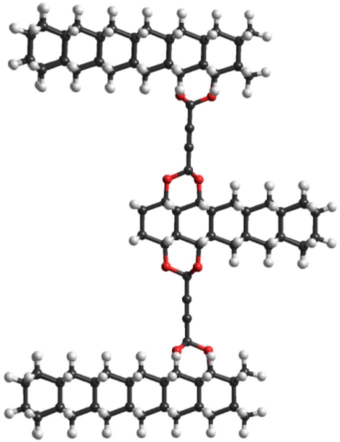
Are there alternatives to electronics?

Mechanical Computing

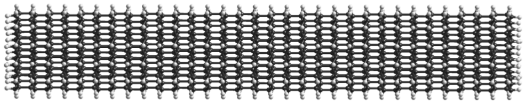
www.imm.org/Reports/rep046.pdf

But!

Snapping, sliding, dragging, squeezing, forcing, pounding, smashing, ringing, tensioning, etc. etc. etc.



+



+ Clocks

Rotary Joints

Links (10 to 20 nm)

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?

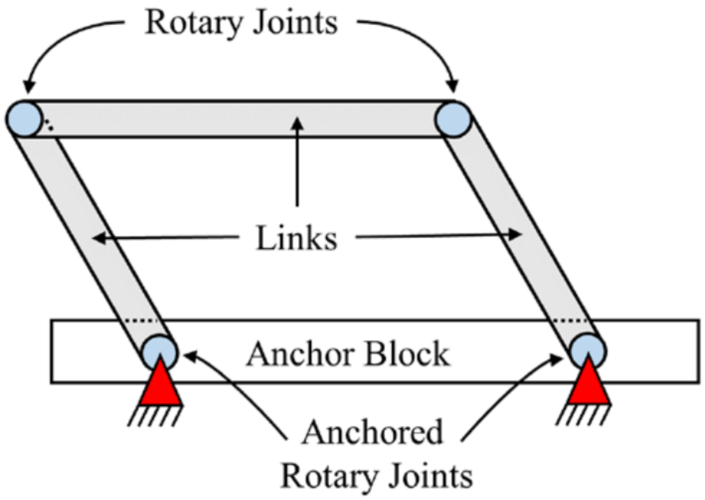
We will define two primitives:

1) A lock

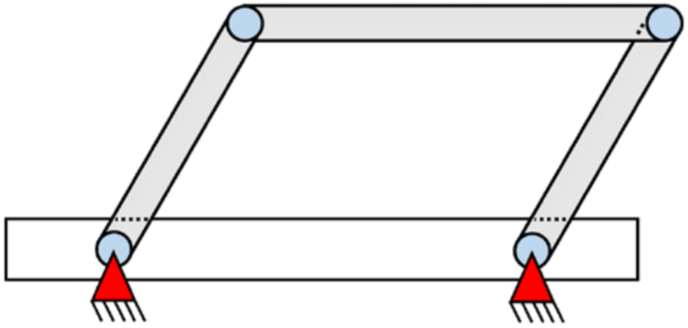
2) A balance

We will then use these two primitives, along with the periodic clocking forces, to implement a shift register.

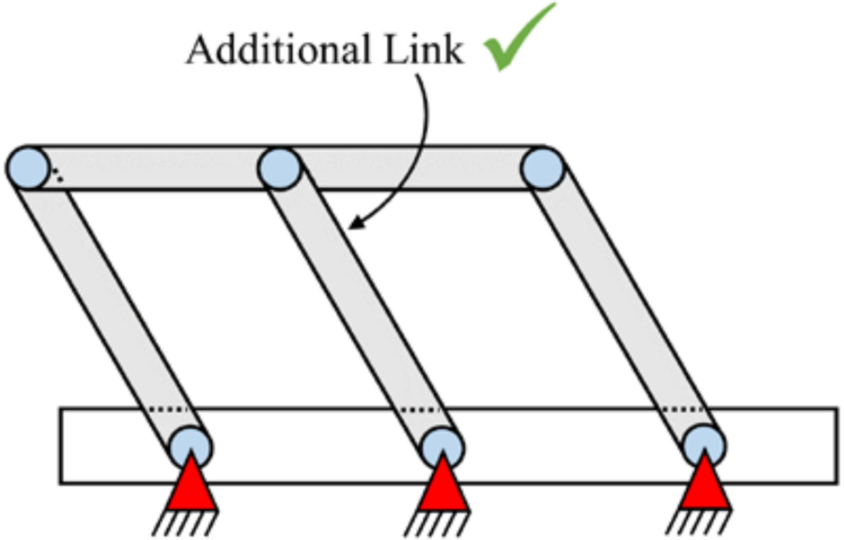
A data link can be in one of two positions. One of these positions is 0, the other is 1.



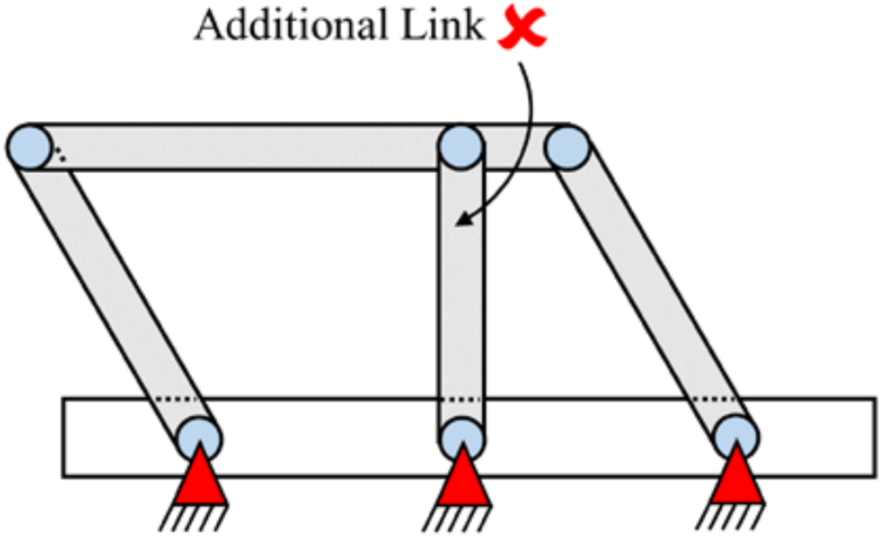
4-Bar Linkage, Left-leaning



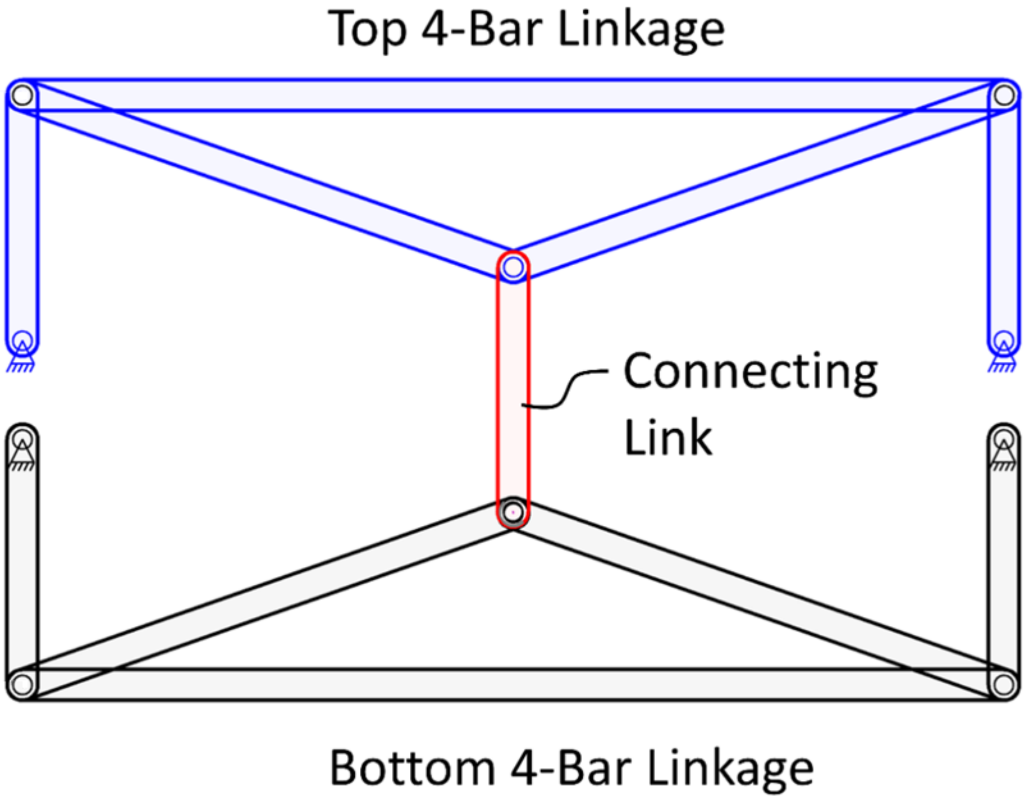
4-Bar Linkage, Right-leaning



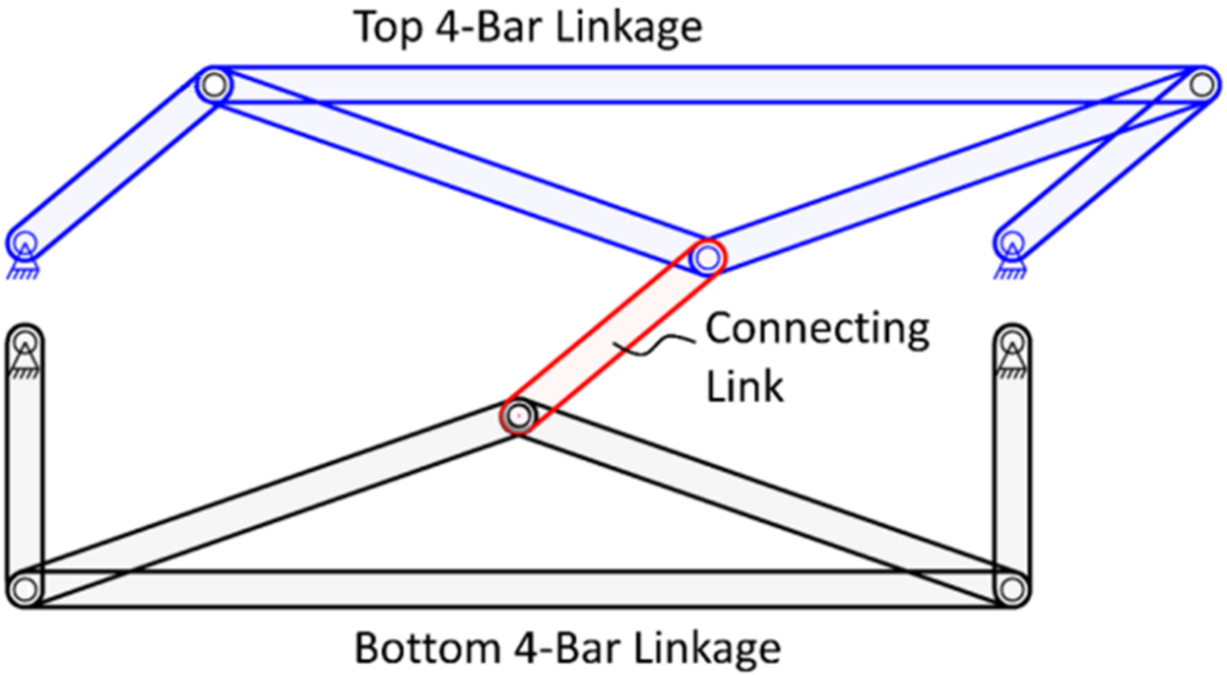
Mobile linkage



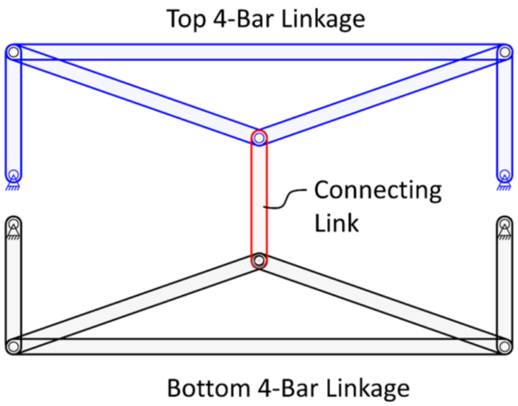
Non-mobile linkage



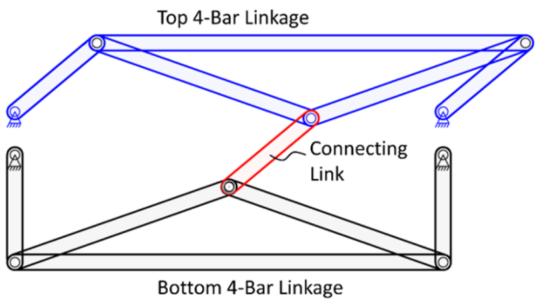
A lock in the (0,0) position



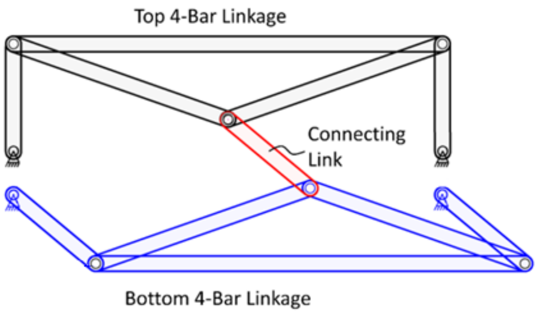
A lock in the (1,0) position



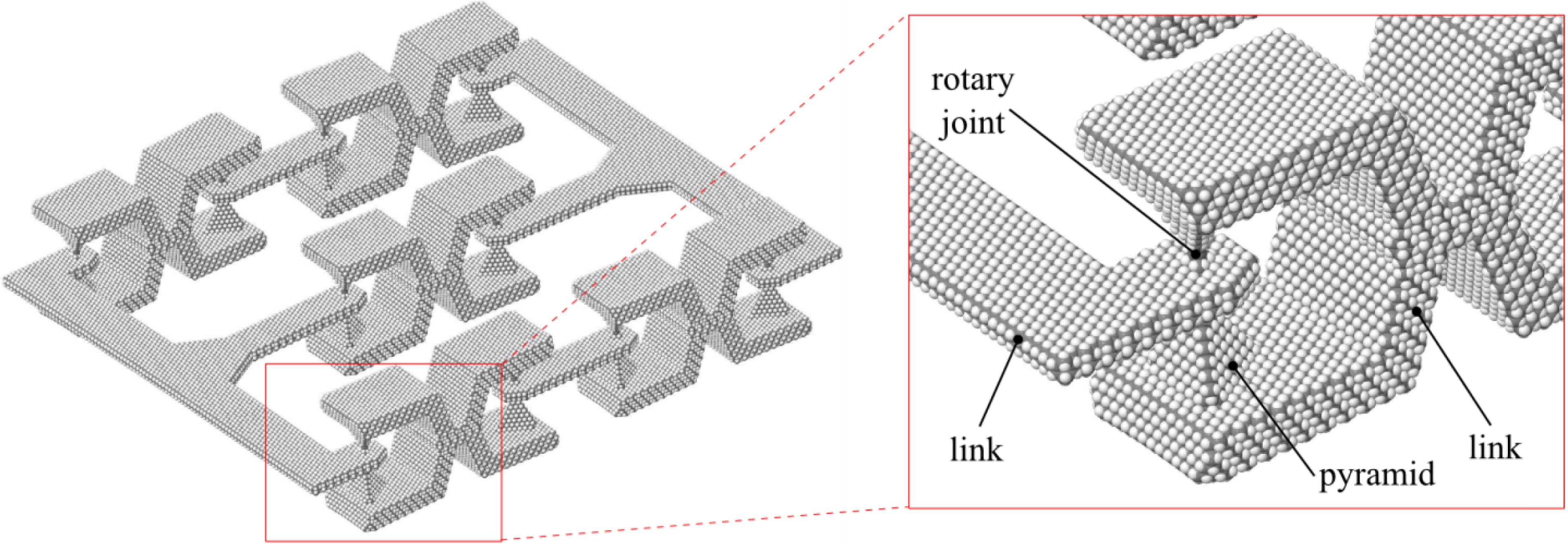
A lock in the (0,0) position



A lock in the (1,0) position

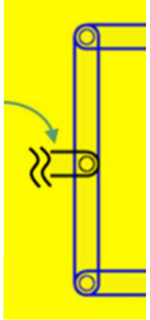


A lock in the (0,1) position

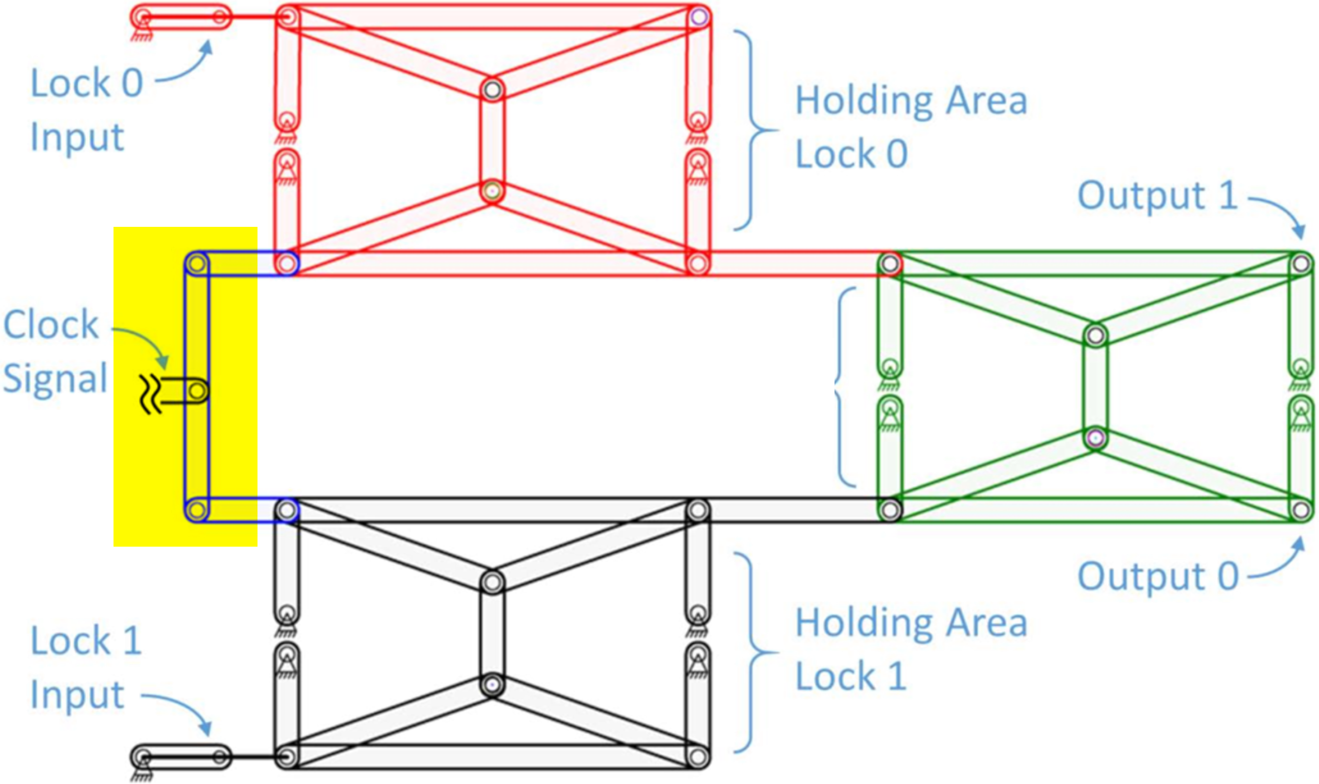

rotary
joint
link
pyramid
link

Balance

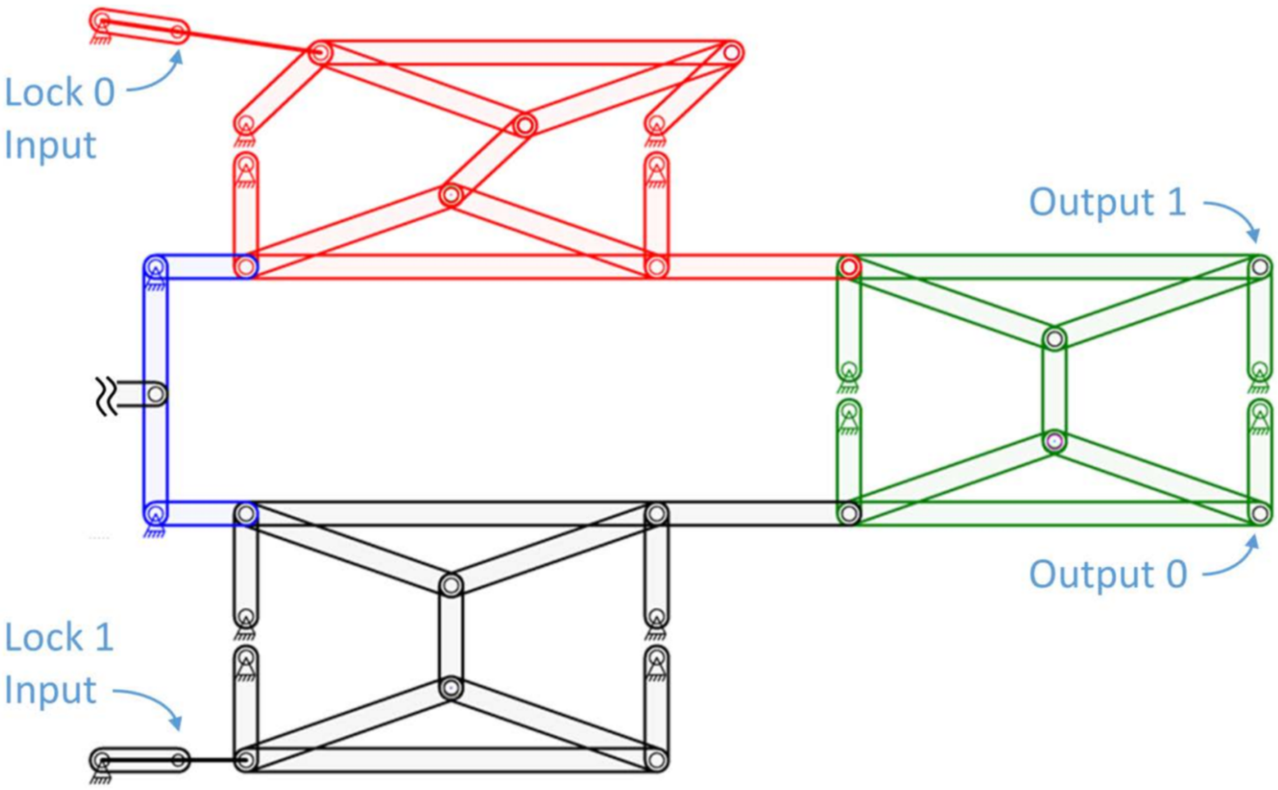
A balance



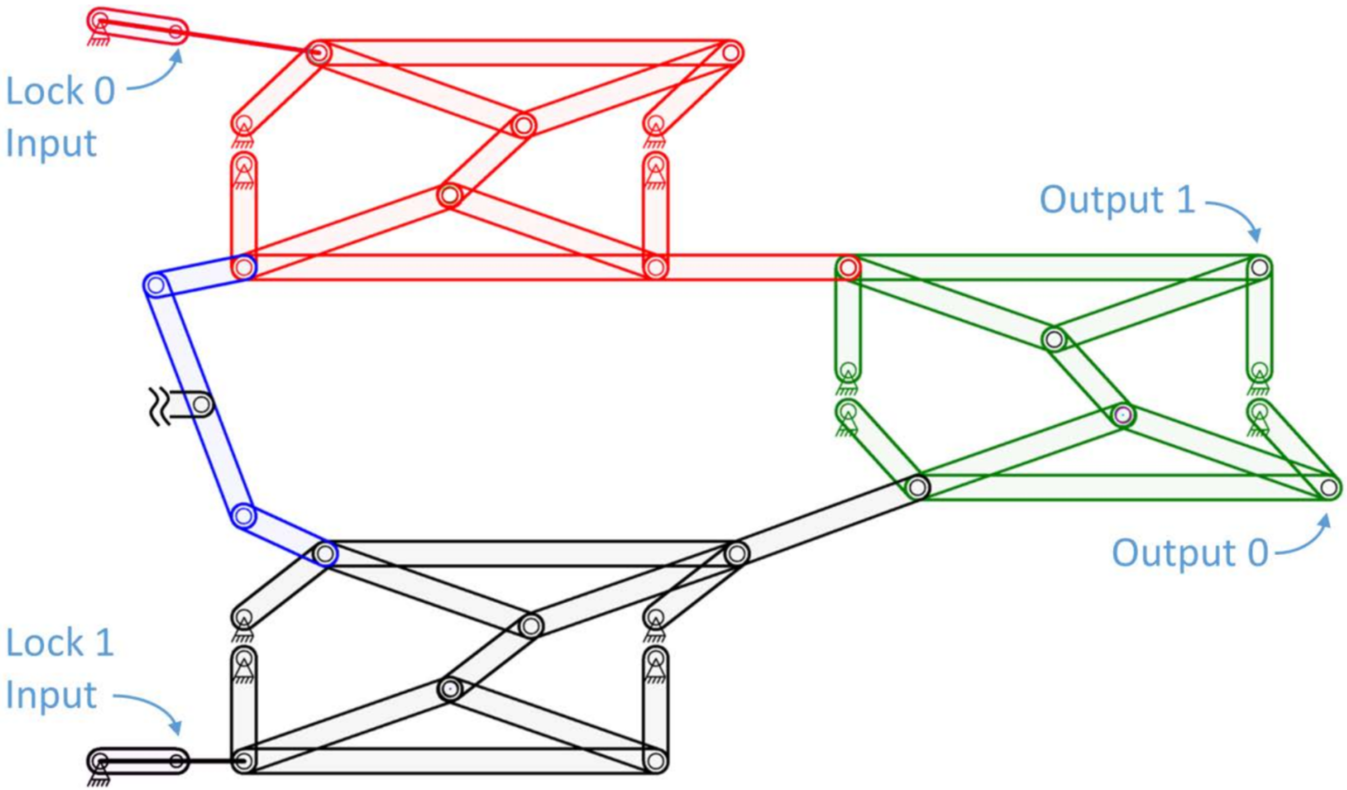
A balance connected to two locks



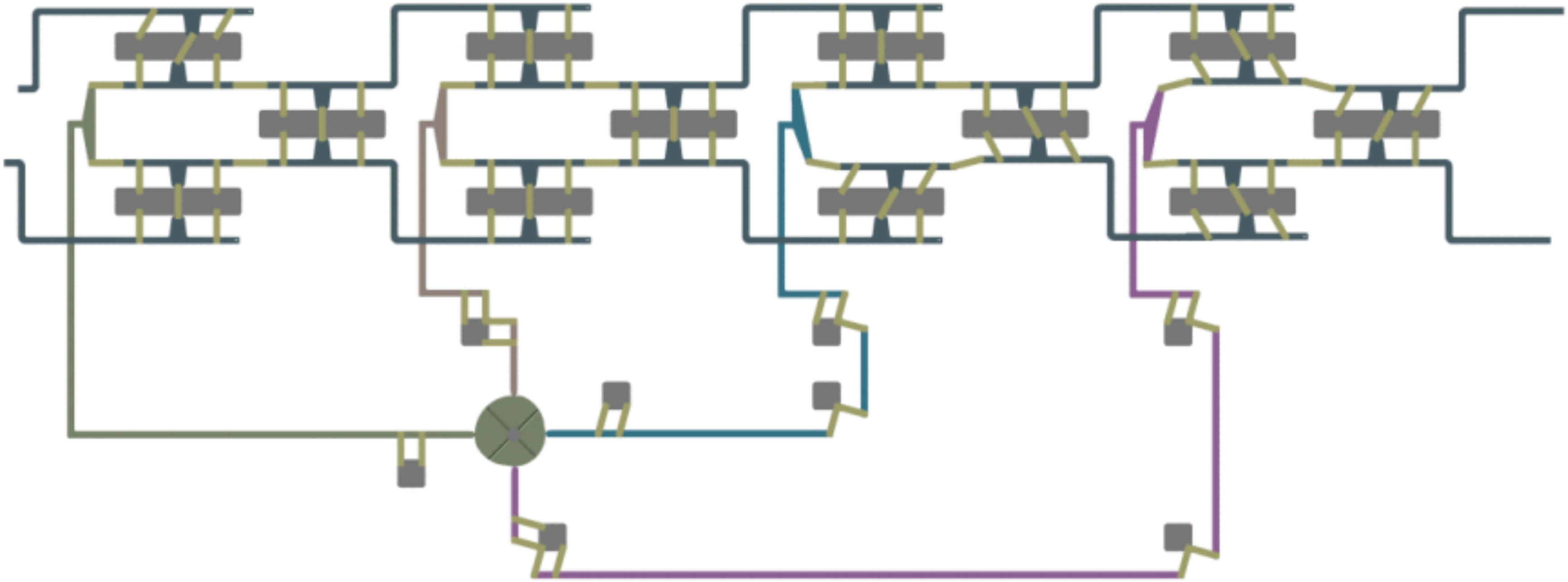
Shift register cell in the (0,0) blank state



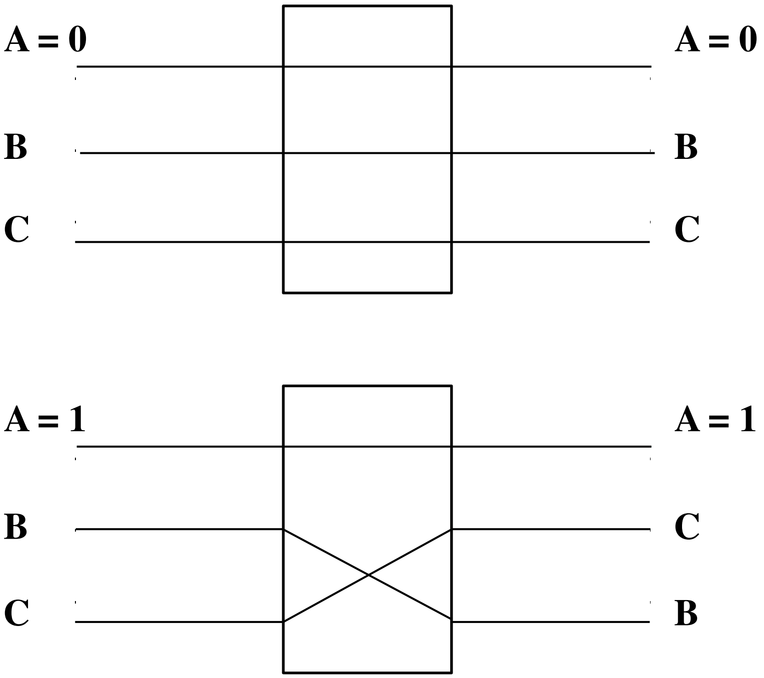
Shift register cell with input (1,0), prior to clock actuation



Shift register cell with input (1,0) after clock actuation

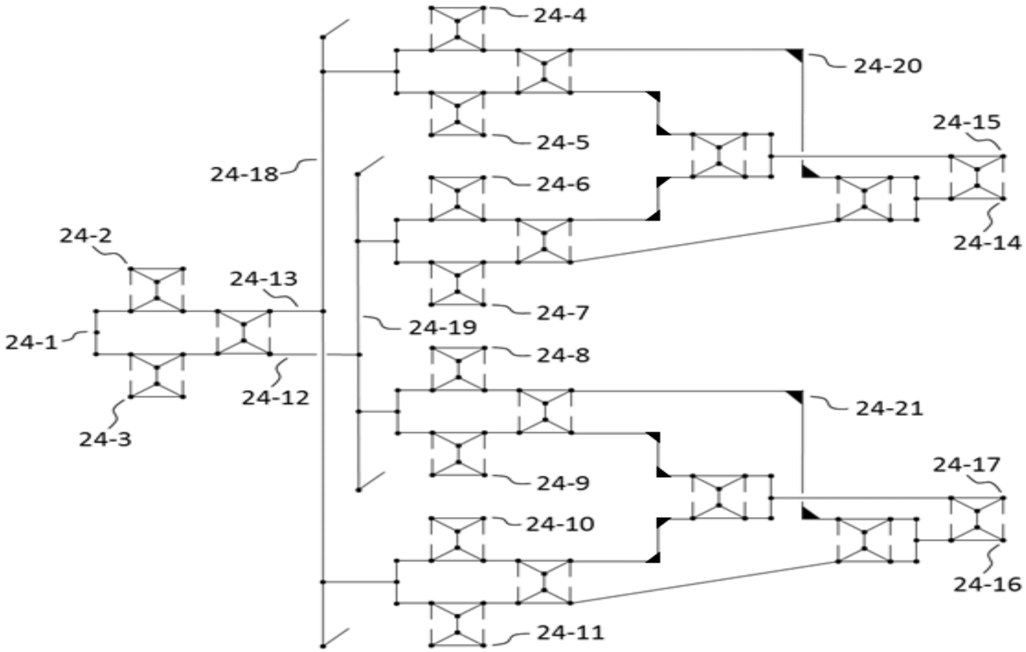


Fredkin Gate
(logically complete)



Mechanical Clocked Fredkin Gate

(from December 2015 patent filing*)

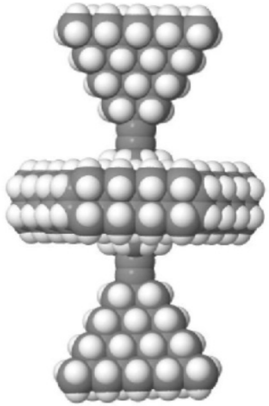


*Mechanical Computing Systems, http://www.merkle.com/papers/MechanicalComputingSystems.pdf

What’s the energy dissipation?

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

Rotary Drag Power Equation



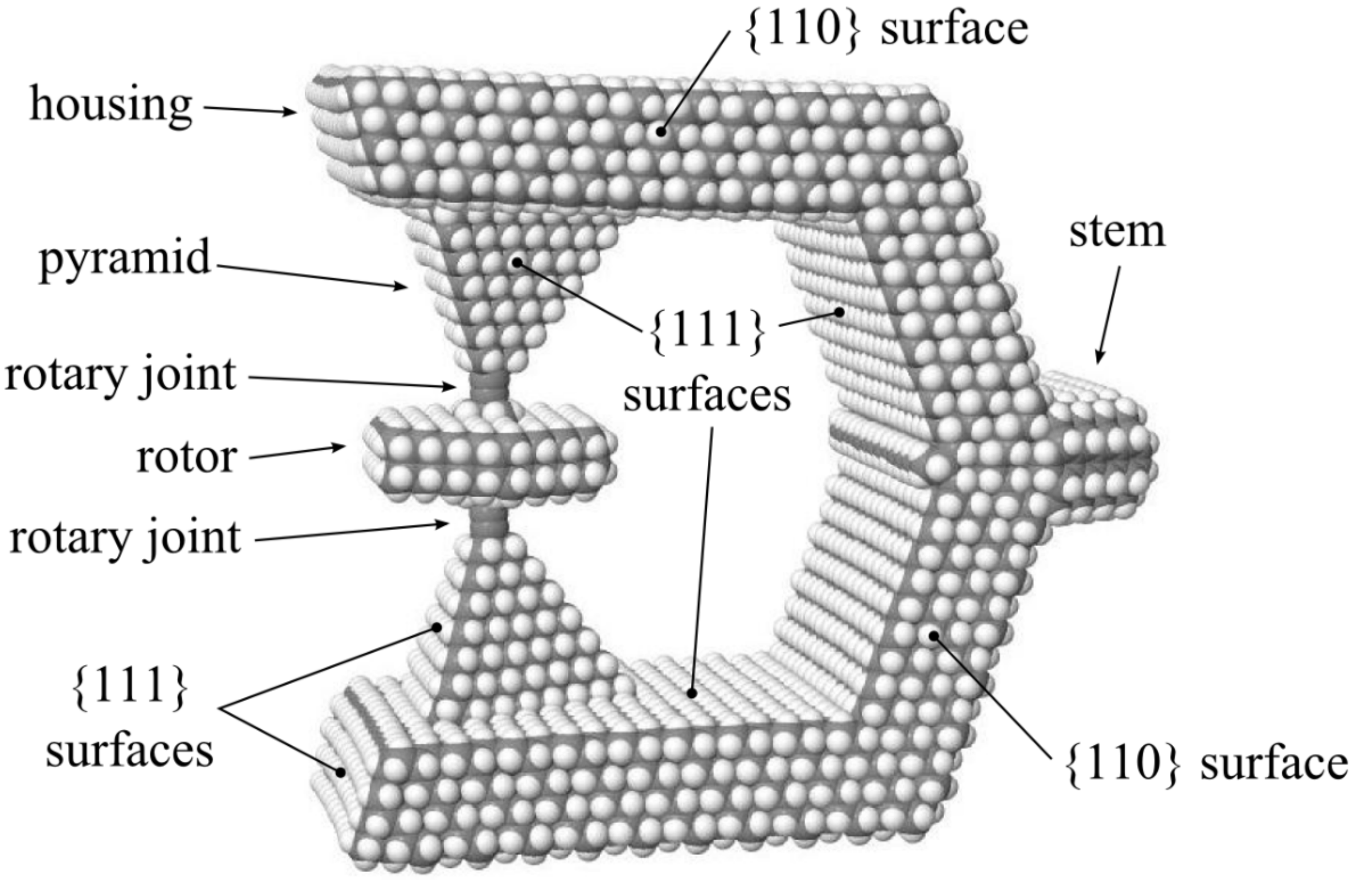
$$P_{rd} = K_{rd}\,\nu_r^{\,2}$$

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)

ν_r is the rotational speed (in radians/second) between the housing and the rotor


{110} surface
housing
stem
pyramid
{111}
surfaces
rotary joint
rotor
rotary joint
{111}
surfaces
{110} surface

$$K_{rd} \sim 2 \times 10^{-35}\ \mathrm{J\ s}$$

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

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

*Floating Point Operations Per Second (https://en.wikipedia.org/wiki/FLOPS)

END OF TALK