Boolean Computation using Oscillators

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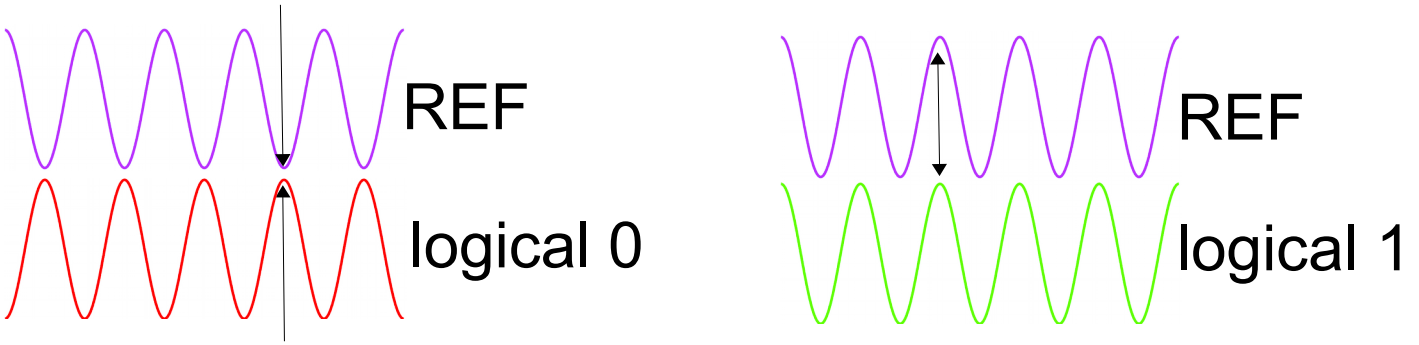
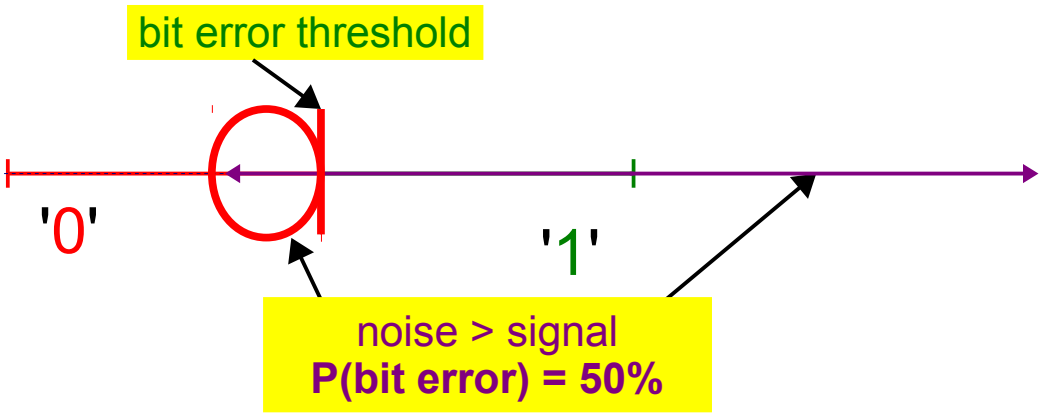
Encoding Bits Using Phase



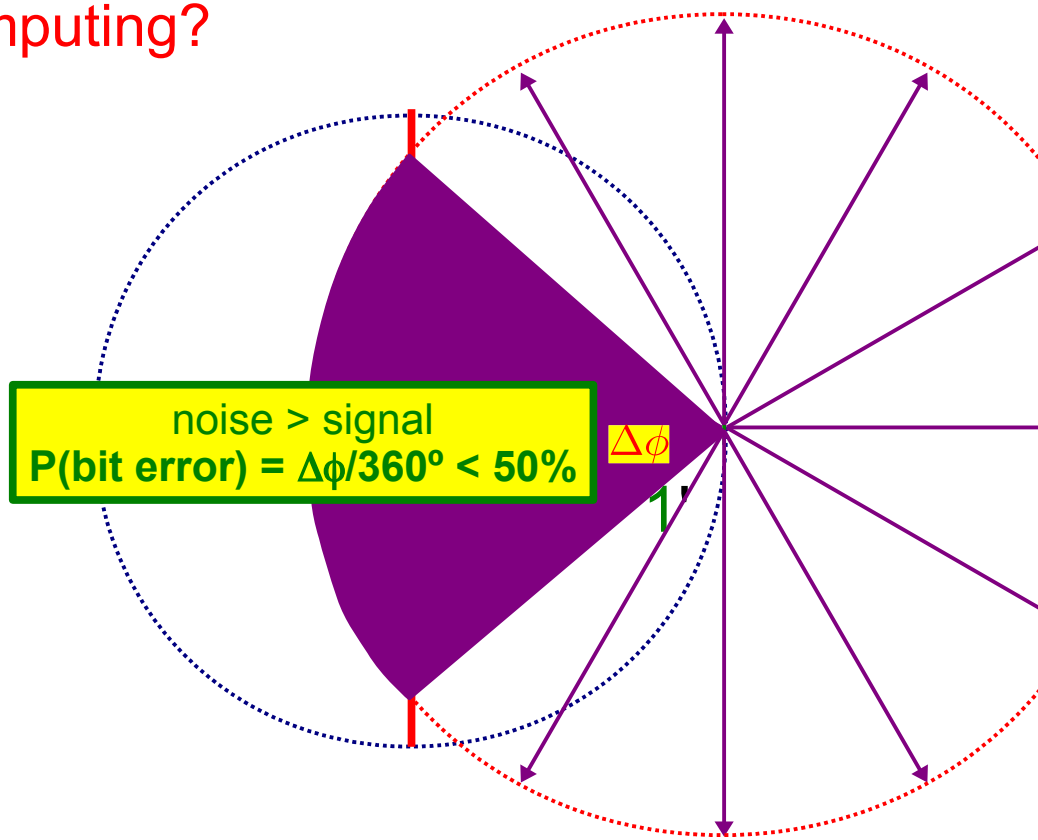
- Can you use this for computing?
- Even if you can: what is the advantage?

Superior Noise Immunity

- loose analogy: PM/FM vs AM in radio
- **Same reason why the BER of BPSK is superior to that of BASK**
- Can you use phase encoding for computing?



noise: level-based encoding



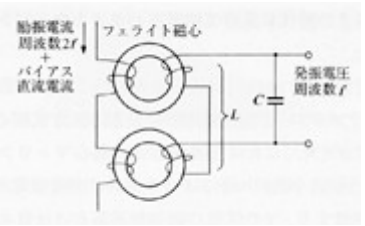
noise: phase-based encoding

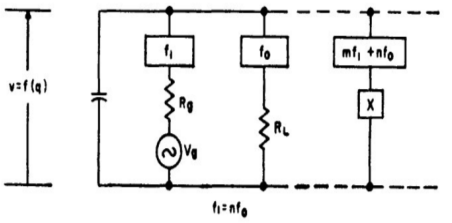
Phase Logic Computers

Eiichi Goto, John von Neumann, 1950s and 60s

- "cheap and reliable"
  - » "widely used in Japan"
- not easy to miniaturise
  - » inductors, iron cores
  - » transistors/ICs dominated
    - – level-based logic

Oi Electric
Parametron X-Ⅸ-01, 1964
Ferro-Electronic Calculator



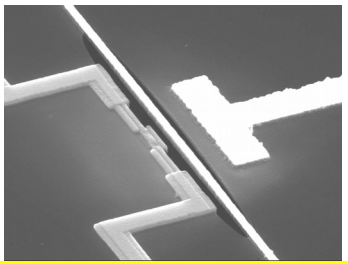


Phase Based Logic:
underlying circuitry/components
have been **difficult to miniaturise**
or **impractical for integration**

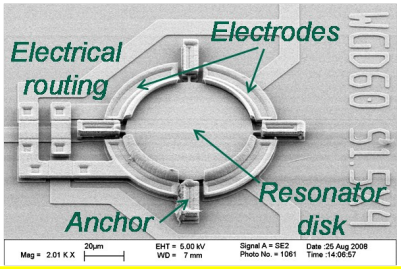
New Result: (almost) Any Oscillator will Do

details: Wang/Roychowdhury, "PHLOGON: Phase-based LOGic using Oscillatory Nano-systems". UCNC, 2014.
Roychowdhury, "Boolean Computation Using Self-Sustaining Nonlinear Oscillators". arXiv, 2014.

MEMS/NEMS

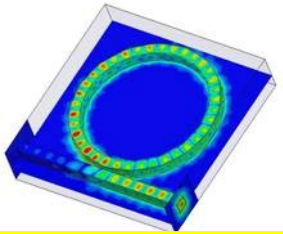


nanoswitch relaxation osc.



MEMS resonator osc.

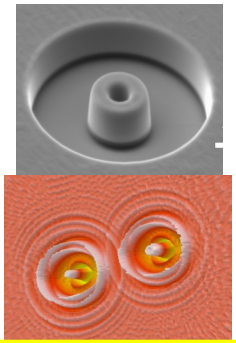
opto-electronic



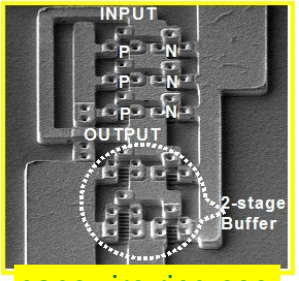
opto-resonator laser

VCSELs

novel nanodevices

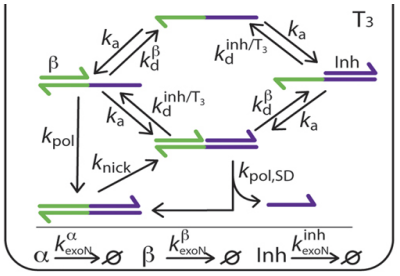


spin-torque

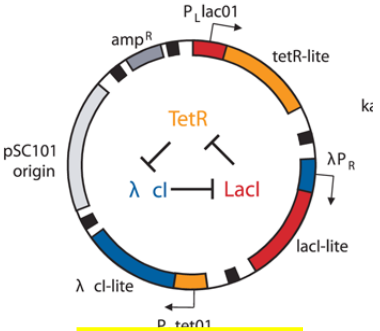


nanowire ring osc.

synth. bio. (DNA)

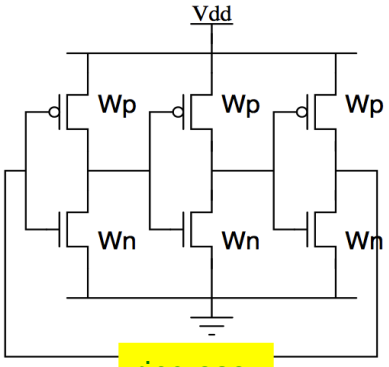


oligator

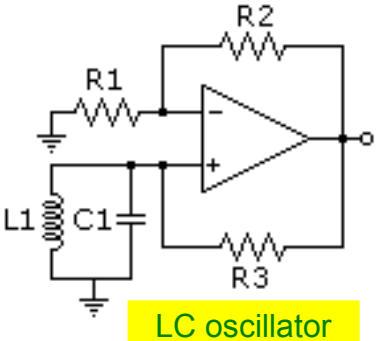


repressilator

CMOS/electronic



ring osc.

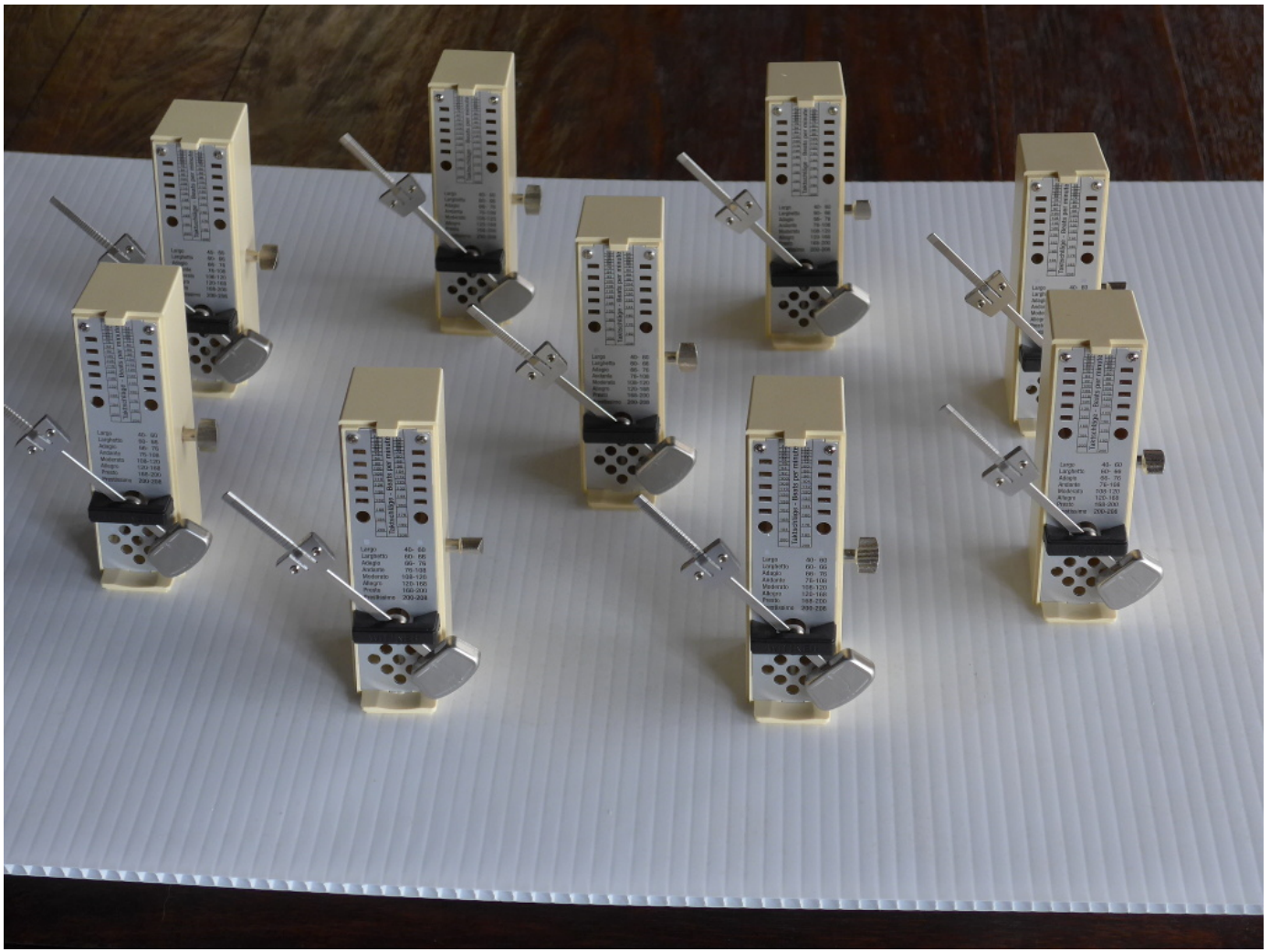


LC oscillator

many are integrable and nano-scale

Underlying Mechanism: Injection Locking

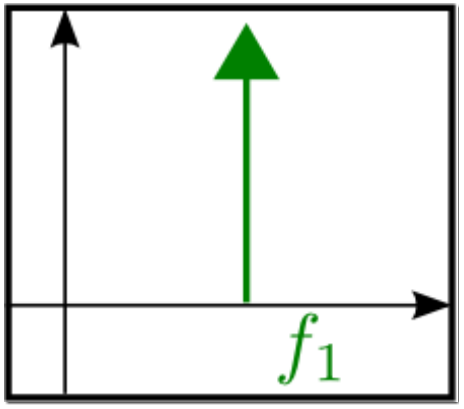
- Oscillators can synchronize in phase/frequency



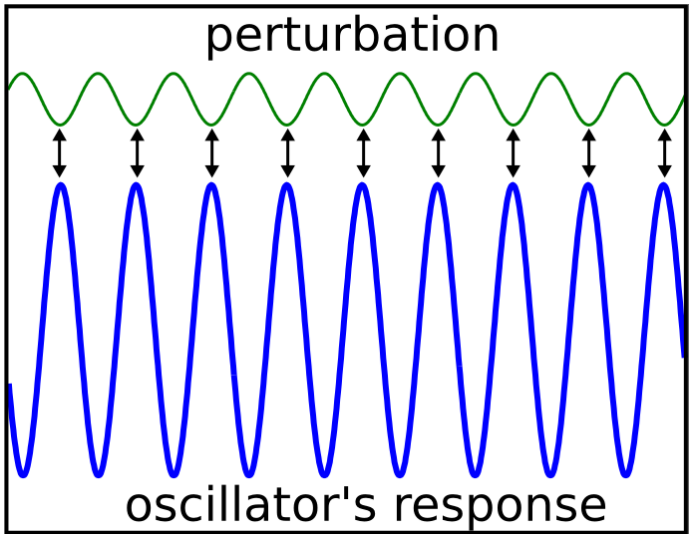
- **we use a variant: sub-harmonic injection locking**

Underlying Mechanism: Injection Locking

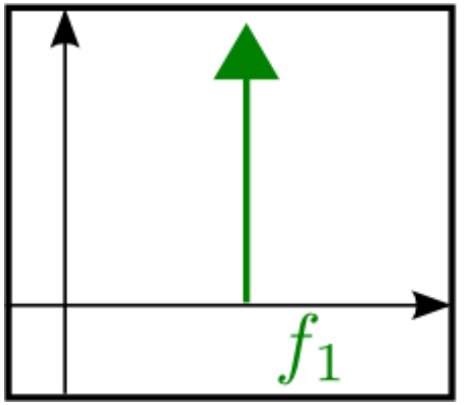
Injection Locking



phase lock



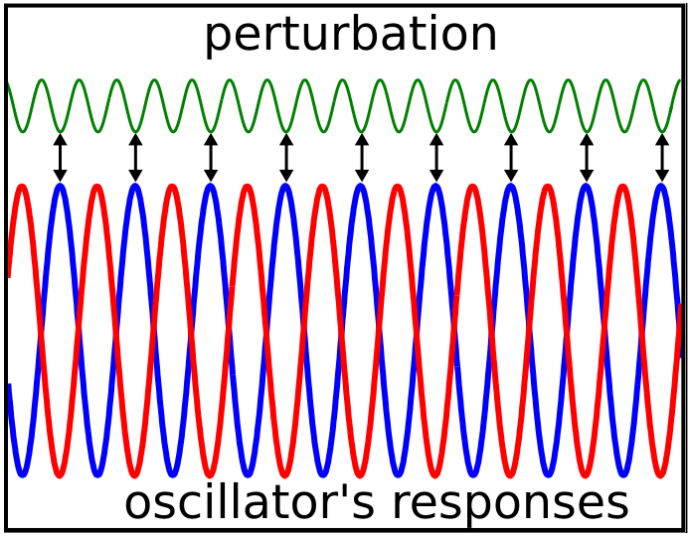
Sub-harmonic Injection Locking (SHIL)



lock 1

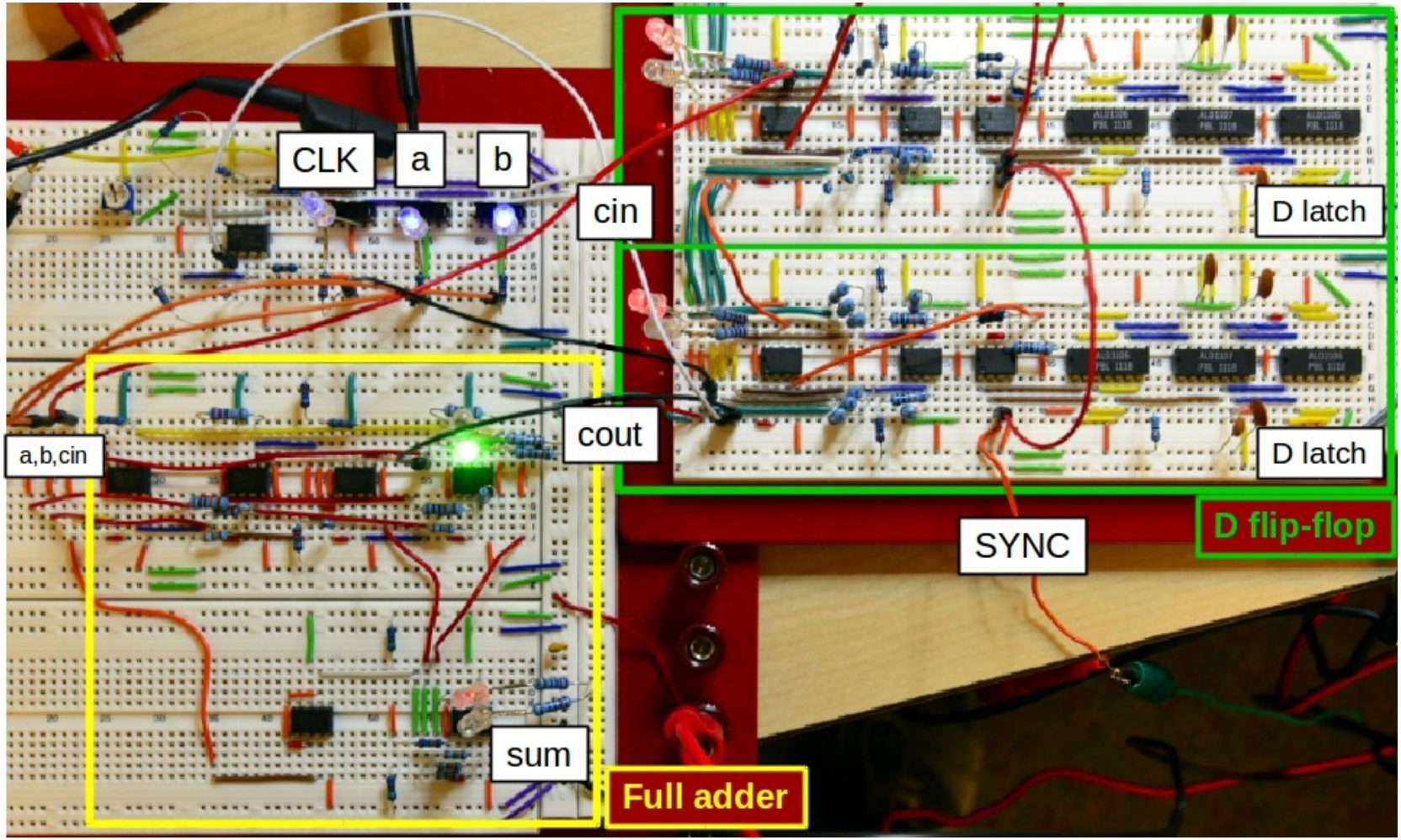
180° phase shift

lock 2

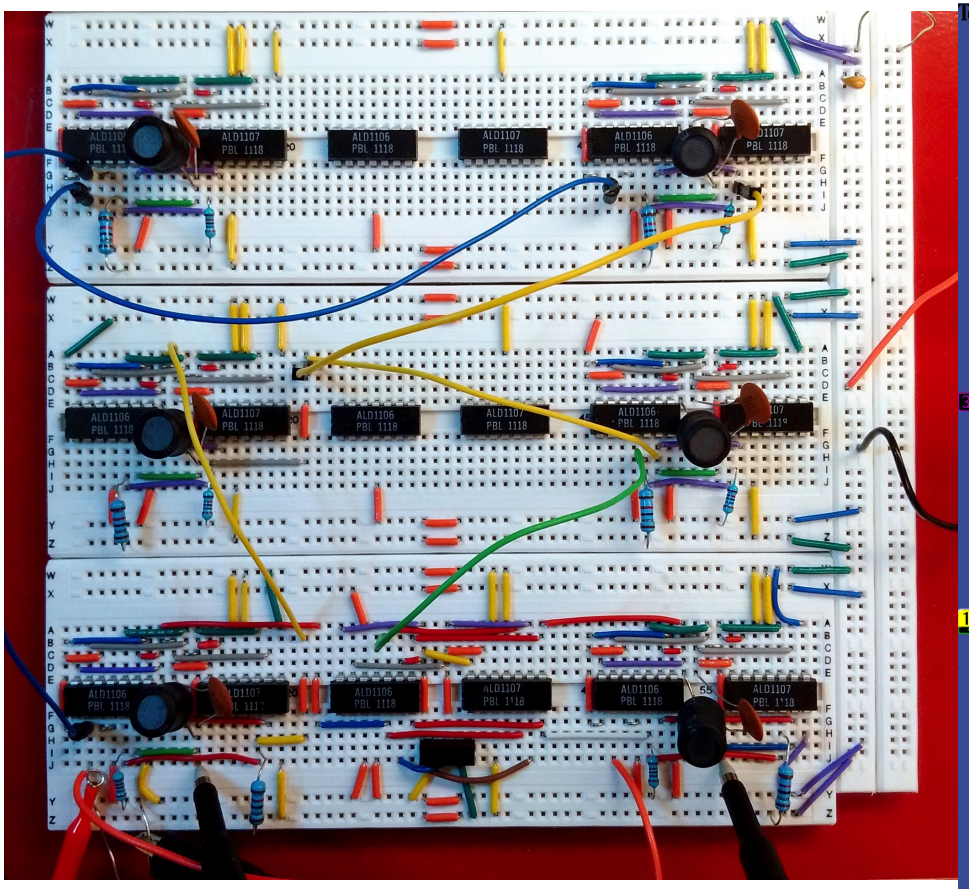


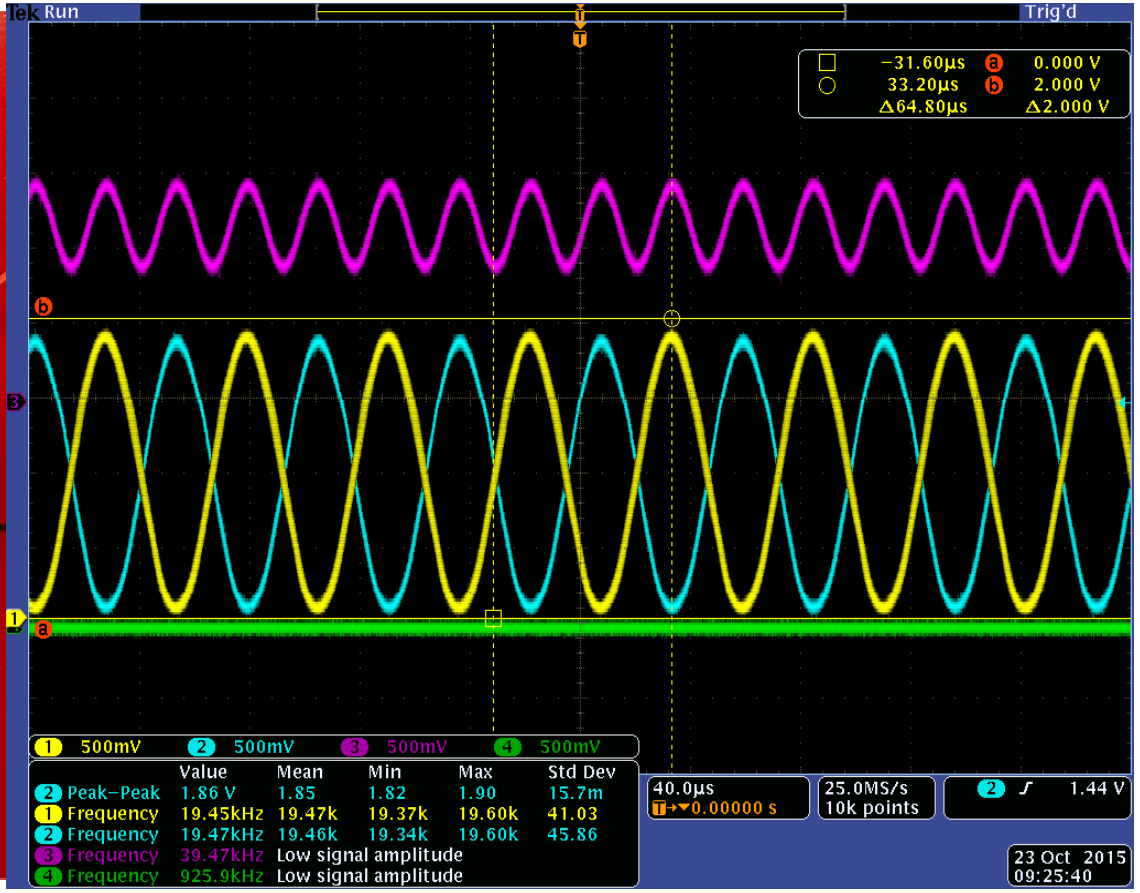
First Phase Logic FSM with Oscillators

- **PHLOGON: PHase LOGic using Oscillatory Nanosystems** using **CMOS ring oscillators**

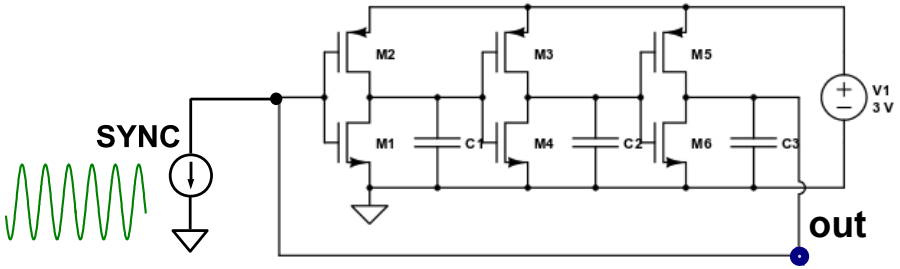


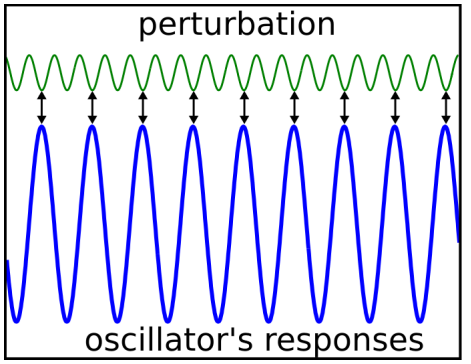
Prototype with CMOS LC Oscillators





Simulating SHIL of Oscillators

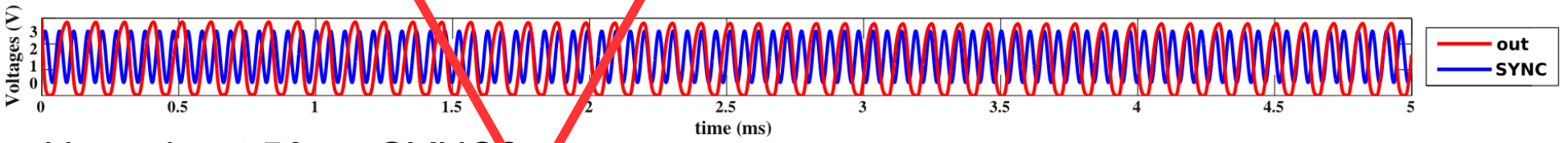




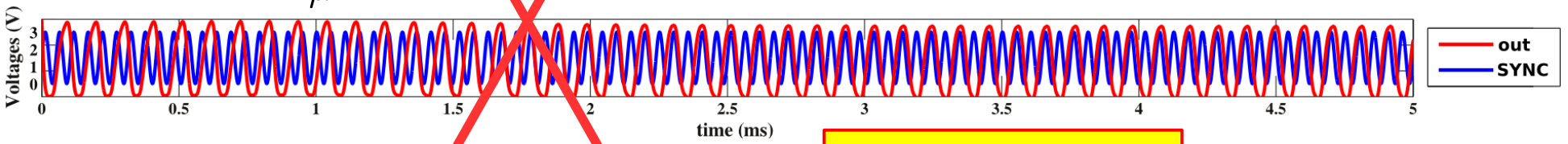
Sub-harmonic Injection Locking (SHIL)

Standard SPICE transient simulation

Is SHIL happening with 20μA SYNC?

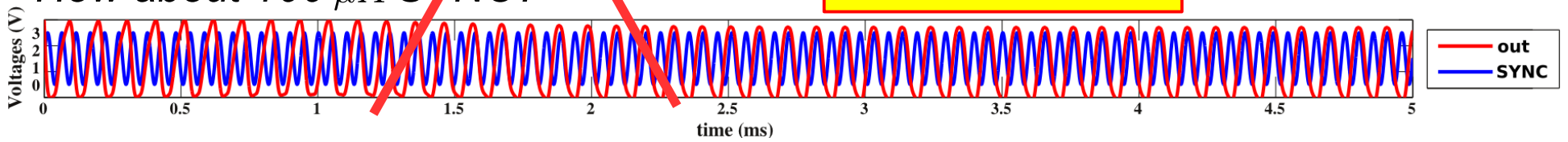


How about 50 μA SYNC?



hard to observe SHIL

How about 100 μA SYNC?



inefficient

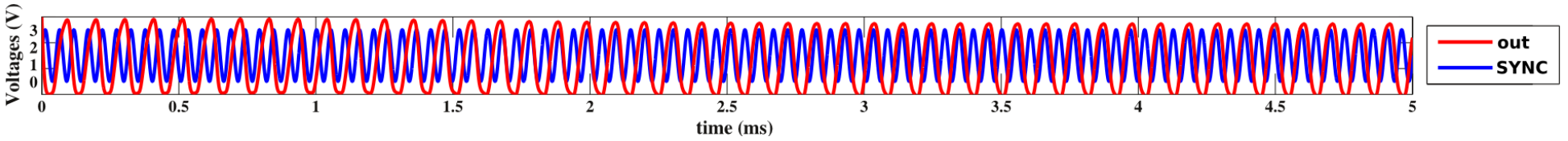
unbounded error in phase

not much insight into design

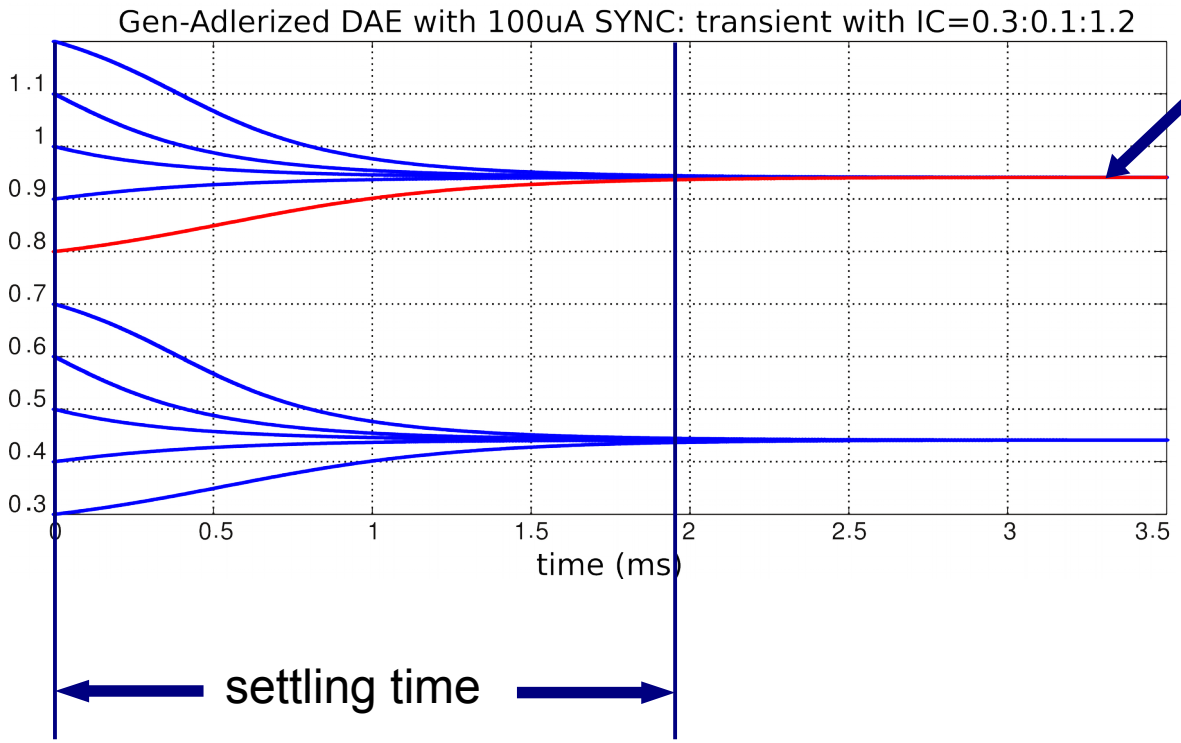
Design tools with phase macromodel analyses

Phase-macromodel-based Analyses

Standard SPICE transient simulation



Phase-based simulation



SHIL occurs: curve "flattens"

"locked phase error"

$\Delta\phi$

Generalized Adler's Equation

$$\frac{d}{dt}\Delta\phi(t) = f_0 - f_1 + f_0 \cdot g(\Delta\phi(t))$$

$$g(\Delta\phi(t)) = \int_0^1 \vec{v}_1^T(\tau + \Delta\phi(t)) \cdot \vec{b}_1(\tau) d\tau$$

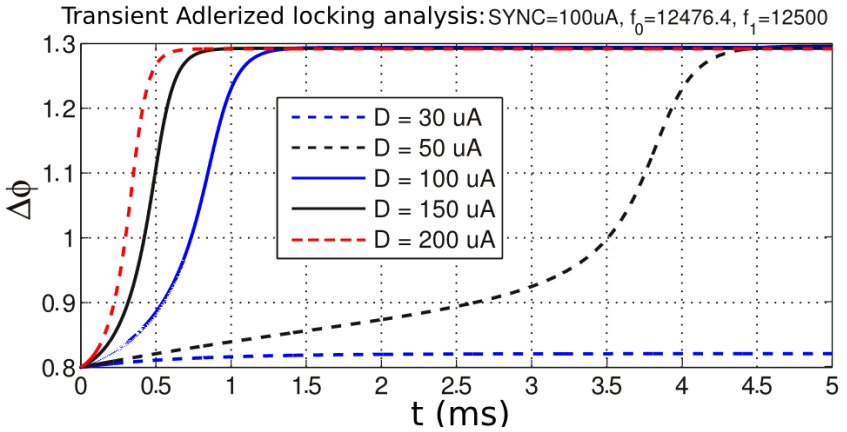
Perturbation Projection Vector (PPV)

details: Bhansali/Roychowdhury, "Gen-Adler: the Generalized Adler's equation for injection locking analysis in oscillators". Proc. ASPDAC, 2009.

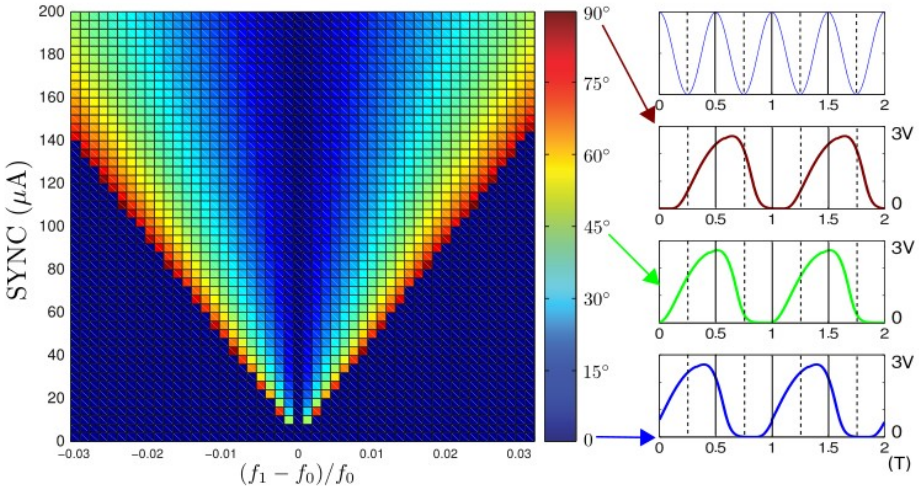
More Capabilities of the Design Tools

details: Wang/Roychowdhury, “Design Tools for Oscillator-based Computing Systems”, DAC, 2015.

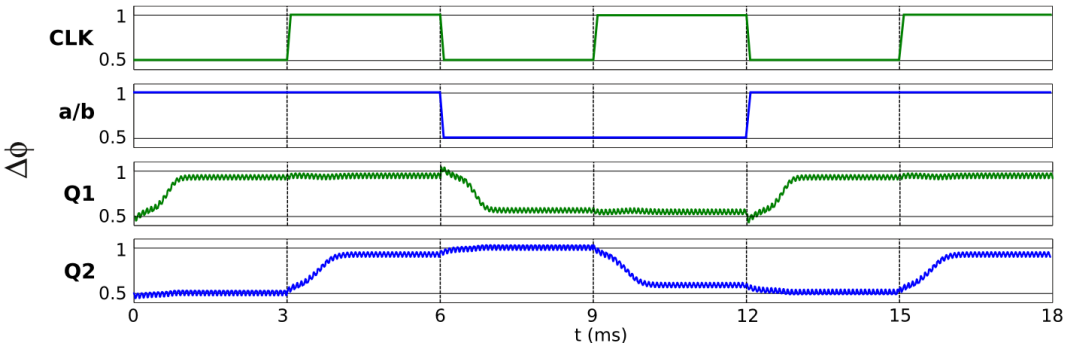
Timing of phase-based D latch



Locked phase error vs. variations in oscillator natural frequency

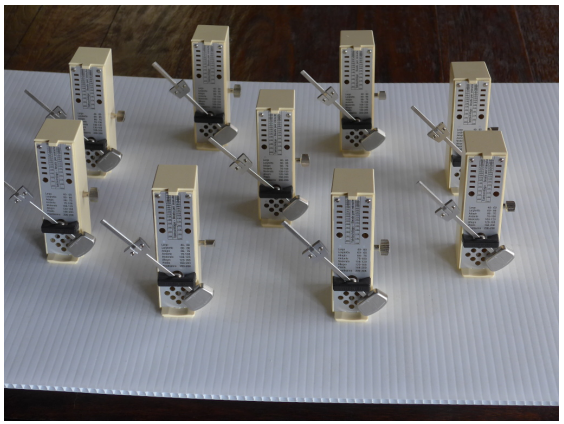


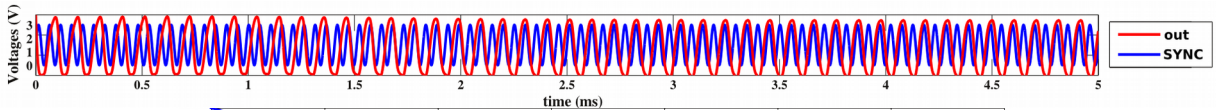
Full system transient in phase domain

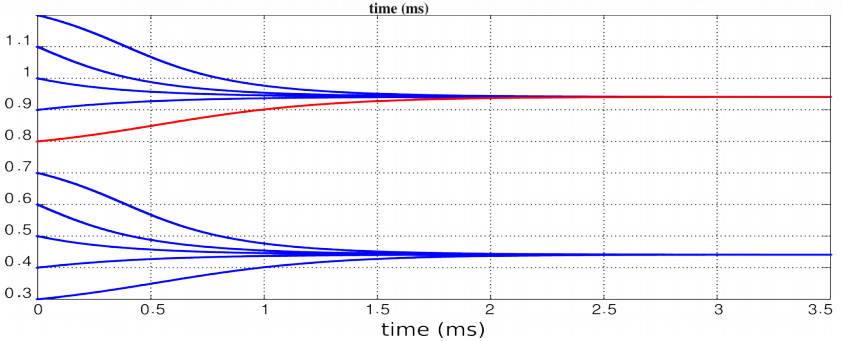


open-source release: **PHLOGON.eecs.berkeley.edu**

Summary







$\Delta\phi$