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Adiabatic Circuits: A Tutorial Introduction

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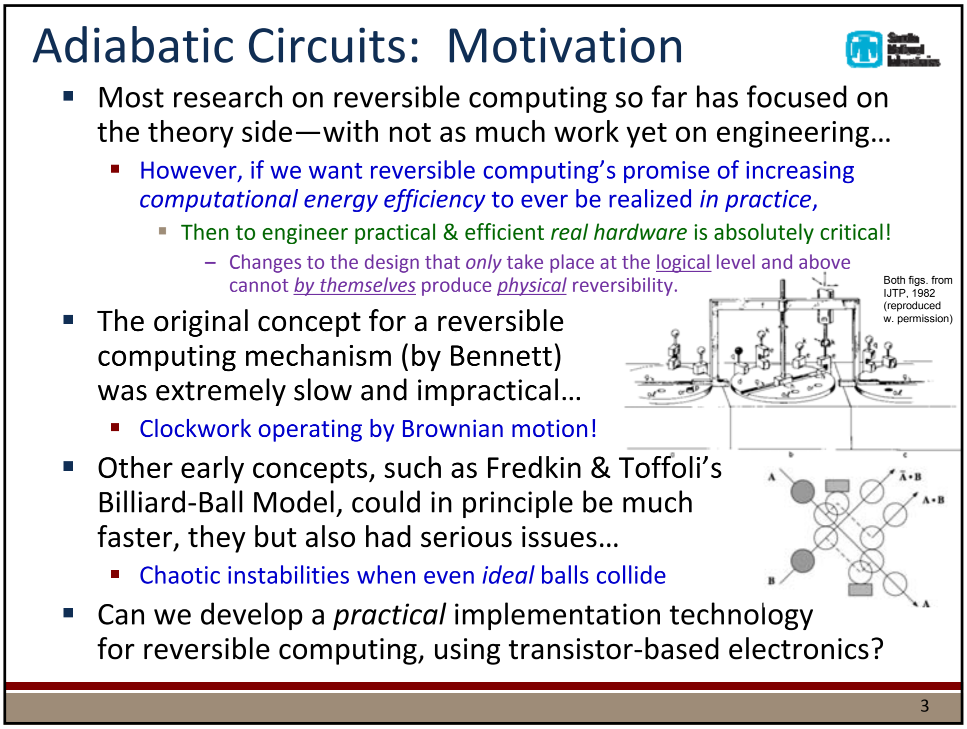
Adiabatic Circuits: Outline of Lecture

- Motivation
  - Adiabatic circuits as an approach to implement reversible computing
- Brief History of Adiabatic Circuits
- Fundamental Principles of Adiabatic Circuits
  - Adiabatic processes – General definitions
  - Adiabatic charge transfer – Energy dissipation analysis
  - Generalized Reversible Computing – Preview of conference talk
    - The correct theoretical foundation for adiabatic design
  - Adiabatic Switching Rules
- Elements of Adiabatic Logic Design
  - Adiabatic two-level and split-level gates
  - Dynamic and static latching
  - Retractile combinational circuits
  - Pipelined sequential circuits
- Power/Clock Generation
  - Strategies for resonator design
- Conclusion

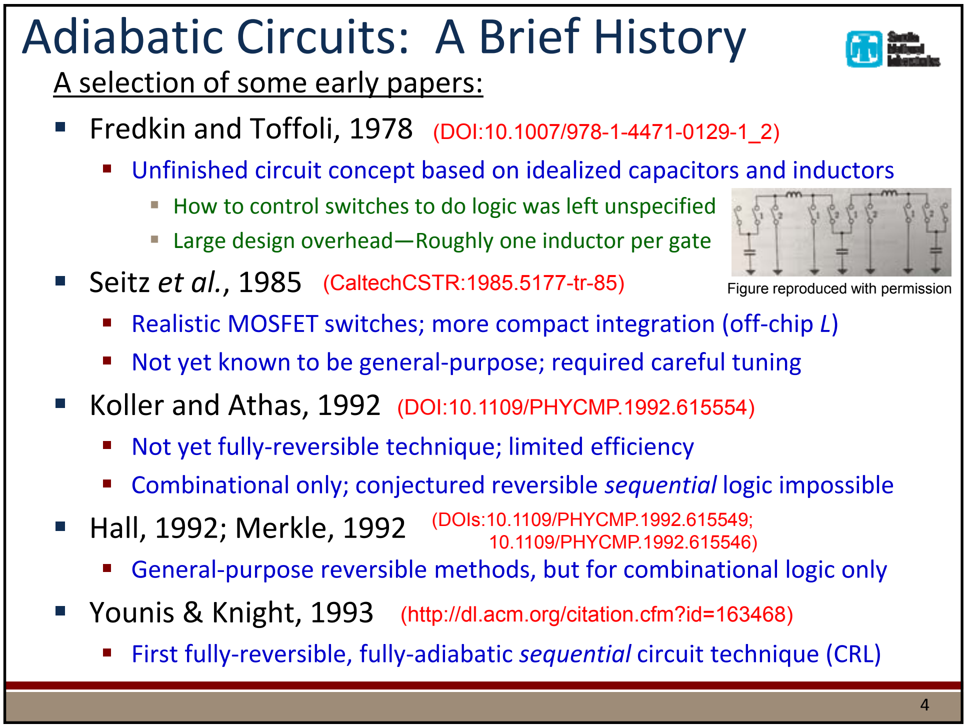


Adiabatic Circuits: Motivation

- Most research on reversible computing so far has focused on the theory side—with not as much work yet on engineering…
  - However, if we want reversible computing's promise of increasing *computational energy efficiency* to ever be realized *in practice*,
    - Then to engineer practical & efficient *real hardware* is absolutely critical!
      - Changes to the design that *only* take place at the logical level and above cannot *by themselves* produce *physical* reversibility.
- The original concept for a reversible computing mechanism (by Bennett) was extremely slow and impractical…
  - Clockwork operating by Brownian motion!
- Other early concepts, such as Fredkin & Toffoli's Billiard-Ball Model, could in principle be much faster, they but also had serious issues…
  - Chaotic instabilities when even *ideal* balls collide
- Can we develop a *practical* implementation technology for reversible computing, using transistor-based electronics?

Both figs. from IJTP, 1982 (reproduced w. permission)

3



Adiabatic Circuits: A Brief History

A selection of some early papers:

- Fredkin and Toffoli, 1978 (DOI:10.1007/978-1-4471-0129-1_2)
  - Unfinished circuit concept based on idealized capacitors and inductors
    - How to control switches to do logic was left unspecified
    - Large design overhead—Roughly one inductor per gate
- Seitz *et al.*, 1985 (CaltechCSTR:1985.5177-tr-85)
  - Realistic MOSFET switches; more compact integration (off-chip *L*)
  - Not yet known to be general-purpose; required careful tuning
- Koller and Athas, 1992 (DOI:10.1109/PHYCMP.1992.615554)
  - Not yet fully-reversible technique; limited efficiency
  - Combinational only; conjectured reversible *sequential* logic impossible
- Hall, 1992; Merkle, 1992 (DOIs:10.1109/PHYCMP.1992.615549; 10.1109/PHYCMP.1992.615546)
  - General-purpose reversible methods, but for combinational logic only
- Younis & Knight, 1993 (http://dl.acm.org/citation.cfm?id=163468)
  - First fully-reversible, fully-adiabatic *sequential* circuit technique (CRL)

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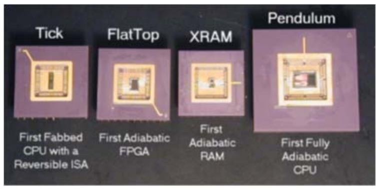
4

Adiabatic Circuits: History, cont.

- Younis & Knight, 1994 (Int'l Workshop on Low-Power Design)
  - Simplified 3-level adiabatic CMOS design family (SCRL)
    - However, the original version of SCRL contained a small non-adiabaticity bug which I discovered in 1997
      - The problem is easily fixed, however
- Subsequent work at MIT, 1995-99
  - Myself and fellow students
  - Various chips designed using SCRL →
  - Reversible processor architectures


Tick
FlatTop
XRAM
Pendulum
First Fabbed CPU with a Reversible ISA
First Adiabatic FPGA
First Adiabatic RAM
First Fully Adiabatic CPU

- Substantial literature throughout the late 90s / early 2000s…
  - Too many different papers / groups to list them all here!
- Researchers recently active in adiabatic circuits include:
  - A couple I know in the US:
    - Greg Snider (Notre Dame)
    - Himanshu Thapliyal (U. Kentucky)
  - Various groups in Europe, India, China, Japan (some here today, hello)…

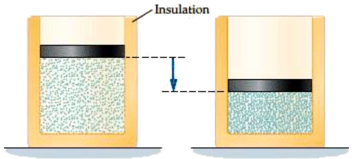
5

Adiabatic Processes: General Definitions

- The word "adiabatic" has a long (>135-year!) history in physics…
  - Derives originally from the Greek *adiabatos* (*άδιάβατος*), "impassable,"
    - In the sense "not to be passed through;" fr. *ά* (not) + *διά* (through) + *βατός* (passable)
  - In practice, in the context of thermodynamics, the word is used to mean:
    - "No [free] energy may pass through the boundary of the system so as to become dissipated out into the system's external environment as heat"
  - For our purposes, we can take it as effectively being a synonym for *isentropic*
    - Meaning, *with the same (unchanging) entropy*
      - Entropy increase = Part of the system's energy is crossing over an abstract boundary from a known/controlled to unknown/uncontrolled state
- For a process to be adiabatic generally requires that the active energy associated with the known/controlled degrees of freedom in the system is *well isolated* from the system's thermal environment, which implies:
  - The process does not happen so *quickly* that uncontrolled modes become excited
    - Rate of the process should be *slow* compared to the system's relaxation timescale
  - But also, it does not happen so *slowly* that the known/controlled energy in the system can leak out from the system to its environment via equilibration processes
    - Time for the process should be *fast* compared for the time for the non-equilibrium aspects of the system to equilibrate with the system's thermal environment
- We can design adiabatic mechanisms that (as they are further refined) approach the ideal of satisfaction of both of these requirements, by
  - Decreasing the relaxation timescale (increase generalized "stiffness" of mechanism)
  - Increasing the equilibration timescale (decrease the rate of energy "leakage")

6

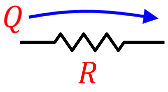
Adiabatic Processes: Example



- Adiabatic compression (or expansion) of an ideal gas under control of a piston in a thermally insulated cylinder…
  - The compression/expansion must be carried out *slowly* enough so as not to excite pressure waves in the gas…
    - Since the energy imparted to such waves would quickly degrade to heat
    - Need: Speed of piston movement << speed of sound in the gas
  - The compression/expansion must be done *quickly* enough so there isn't enough time for heat to be conducted into or out of the cylinder
    - Temperature inside the cylinder would typically be changing as the gas compresses/expands, and is not always the same as environment temp.
      - And, heat conducted from higher→lower temp. yields an entropy increase
    - Time for piston movement << time constant of thermal equilibration

Adiabatic Change Transfer:

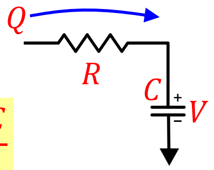
Energy Dissipation Analysis



- Consider passing a total quantity of charge Q through a resistive element of resistance R over a timespan t by means of a constant current, $I = Q/t$.
  - The power dissipation (rate of energy dissipation) in such a current flow is given by $P = IV$, where $V = IR$ (Ohm's Law) is the voltage drop across the resistor.
- The total energy dissipated over time t is therefore:

$$E_{\text{diss}} = P \cdot t = IVt = I^2Rt = (Q/t)^2Rt = Q^2R/t.$$

  - Note the inverse scaling with the time t taken for the charge transfer!
- If the function of the charge transfer is to charge a capacitance C up to the voltage level V, then the quantity of charge transferred is $Q = CV$, and so the energy dissipated can be expressed as:

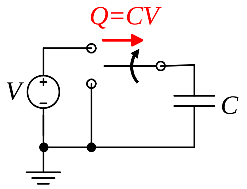


$$E_{\text{diss}} = (CV)^2R/t = C^2V^2R/t = CV^2\frac{RC}{t}$$

Conventional *vs.* Adiabatic Charging

For charging a capacitive load C through a voltage swing V

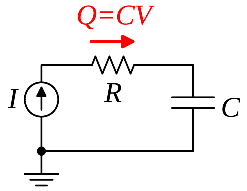
- Conventional charging:
  - Constant *voltage* source



  - Energy dissipated:

$$E_{\text{diss}}^{\text{conv}} = \frac{1}{2}CV^2$$

- Ideal adiabatic charging:
  - Constant *current* source

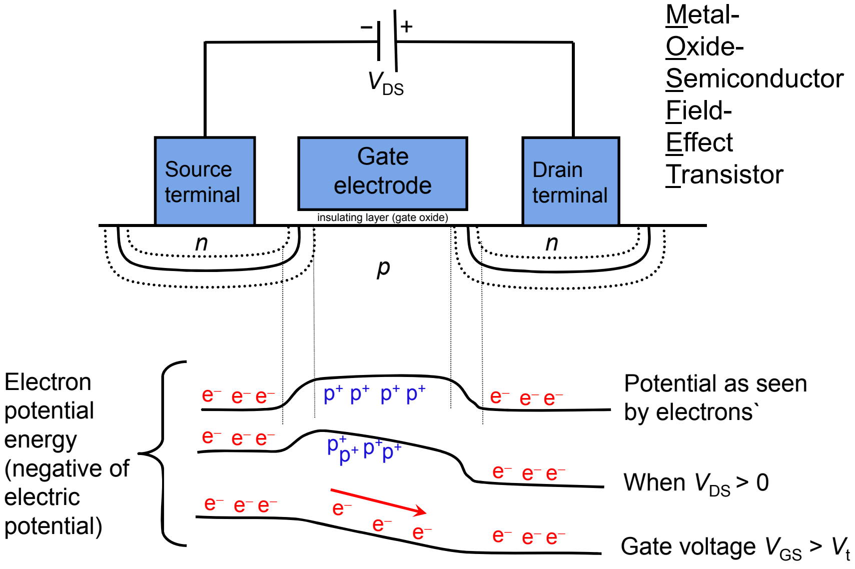


  - Energy dissipated:

$$E_{\text{diss}}^{\text{adia}} = I^2Rt = \frac{Q^2R}{t} = CV^2\frac{RC}{t}$$

Note: Adiabatic charging beats the energy efficiency of conventional by advantage factor: $A = \frac{E_{\text{diss}}^{\text{conv}}}{E_{\text{diss}}^{\text{adia}}} = \frac{1}{2}\frac{t}{RC}$

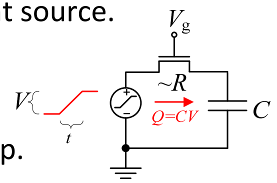
npn MOSFET (*n*-FET)



Metal-
Oxide-
Semiconductor
Field-
Effect
Transistor

Adiabatic Charging via MOSFETs

- Let a voltage ramp *approximate* an ideal current source.
  - The load gets charged *conditionally*, if the MOSFET is turned on (gate voltage $V_g > V + V_t$) during ramp.
    - V_t is the transistor's threshold, typically < ½ volt
- Can discharge the load later using a similar ramp.
  - Either through the same path, or a different path.



$t \gg RC \Rightarrow E_{\text{diss}} \to CV^2 \frac{RC}{t}$

$t \ll RC \Rightarrow E_{\text{diss}} \to \frac{1}{2} CV^2$

Exact formula:

$$E_{\text{diss}} = s\left[1 + s\left(\mathrm{e}^{-1/s} - 1\right)\right]CV^2$$

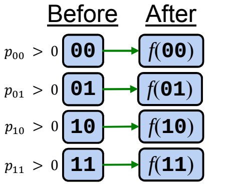
given *speed fraction* $s = RC/t$.

- Note that the (ideal) operation of this circuit approaches *physical reversibility* ($E_{\text{diss}} \to 0$) in the limit $t \to \infty$, but *only* if a certain *precondition* on the initial state is met (namely, $V_g > V_{\max} + V_t$)
  - How does its possible physical reversibility relate to its *computational* function, and to some *appropriate* concept of logical reversibility?
    - Traditional (Landauer/Fredkin/Toffoli) reversible computing theory does **not** adequately address this question, so, we need a more powerful theory!

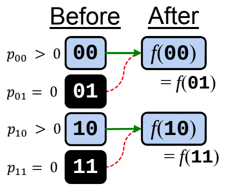
Generalized Reversible Computing

(preview of talk in main conference)

- In contexts where *all* initial computational states can be considered "possible" (*i.e.*, have probability of occurring >0)
  - The traditional definition for logical reversibility of computational operations (*i.e.*, that the transformation of all states is bijective) does correctly identify the logical-level requirements for entropy not to be ejected from the computational state as a result of the operation…
- **BUT**, in operating contexts wherein some of the initial computational states *never arise* (guaranteed by the system design), those states have *probability equal to 0*, and thus *cannot contribute* to the entropy ejected at all – those states *can* merge with others reversibly!
  - Thus, the *correct* statement of the minimum logical-level requirements for reversibility is simply that only *the **subset** of initial states that meet a particular assumed precondition that is obeyed with certainty* must be transformed one-to-one onto final states.
    - In such a case, we say that we have a *logically reversible computation* performing an operation that is itself only *conditionally* (logically) reversible.



Unconditionally logically reversible operation



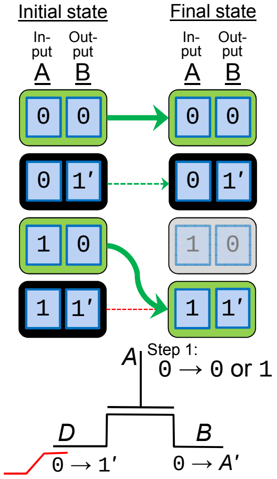
Conditioned logically reversible operation, with the assumed precondition that the 2nd input bit = **0**

Why GRC is the right theoretical foundation for modeling reversible computation in adiabatic circuits!

- E.g.: Even *a single MOSFET* (operated adiabatically) can do a certain (conditioned) reversible COPY operation…
  - Operation sequence is as follows:
    0. Driving node D is initially statically held at 0, input *A* also 0.
    1. Input A is externally supplied (D&B connected iff *A* is high)
    2. Externally transition driver D from 0 to (weak) logic high 1′
    3. Voltage level on node B follows D iff A is strong logic high (**1**)
       - B is then afterwards logically equal to A (with a weak swing)
  - Note: Given a (strong) assumed precondition of $\bar{B}$,
    - *i.e.*, if all initial states with $B = 1$ have prob. 0,
    - this indeed performs a reversible COPY operation, $\mathrm{rCOPY}(A, B \mid \bar{B}\ )$.
  - Note: The output in this case is not full-swing,
    - In this diagram, primes (′) denote reduced-voltage logic high signals
      - If we need full-swing outputs, we can use a transmission gate (parallel nFET/pFET pair) with complementary controls
  - A notation precisely describing this operation's semantics is:
    - $[\overline{AB}]$ if $B = 0$ then $B \coloneqq A$ *(else, leave state unchanged)*
      - The expression $\overline{AB}$ in brackets gives the ***precondition for reversibility*** for the entire operation (the operation is both logically reversible and asymptotically thermodynamically reversible unless $A = B = 1$).
      - The remainder of the statement describes exactly how the state will be transformed in all cases (even if the precondition is not met).
- Note: Traditional reversible computing theory based on unconditionally reversible operations is insufficient to express the logical/physical reversibility of this operation!

Reversible COPY

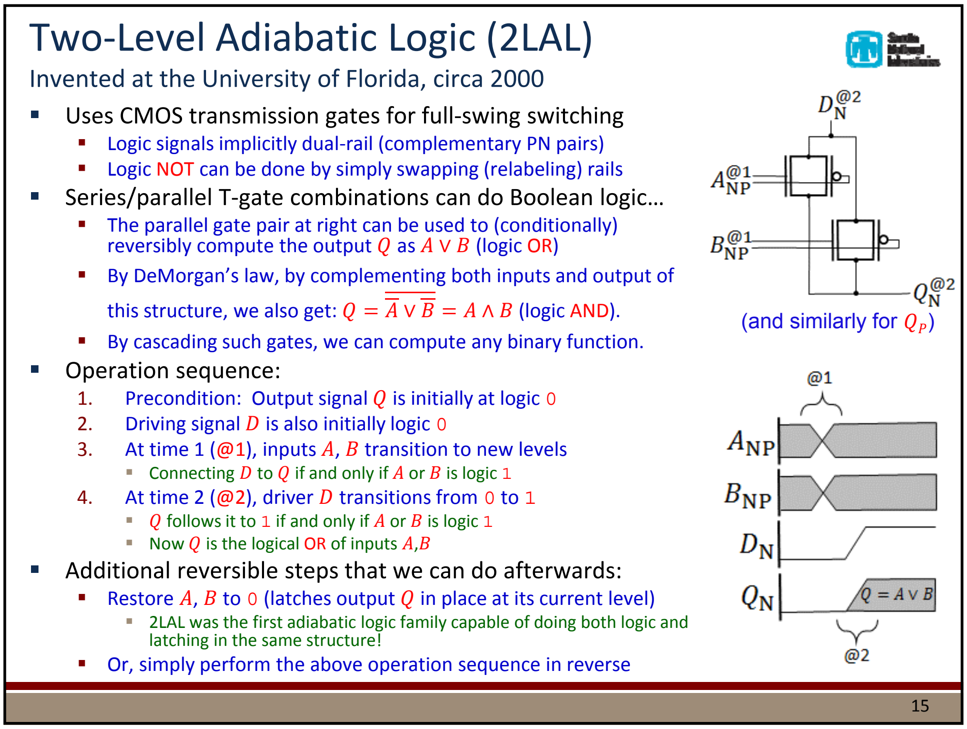
$\mathrm{rCOPY}(A, B \mid \bar{B}\ )$



(Here, D and B have a reduced swing, but a T-gate can easily fix this)

All truly, fully adiabatic circuits are conditionally reversible!

- "Dry switching" rules for designing truly adiabatic circuits:
  - Never close a switch when there's a voltage ≠0 between its terminals
    - E.g., don't turn on a transistor when $V_{\mathrm{DS}} \neq 0$.
  - Never open a switch when there's a current passing through it.
    - E.g., don't turn off a transistor when $I_{\mathrm{DS}} \neq 0$.
    - Only exception to this rule: If there's an alternate path for the current.
  - Never pass current through diodes (which have a voltage drop)
- Violating any of these rules leads to significant dissipation!
- **Theorem:** The operation of a switching circuit carries out a (conditionally) logically reversible computation, in any operation context where the above rules are always satisfied.
  - *It's impossible to erase information in any truly, fully adiabatic logic operation.* → Logically-reversible computing is key to adiabatic design
    - But, the *right* definition of "logically reversible" is our generalized one!

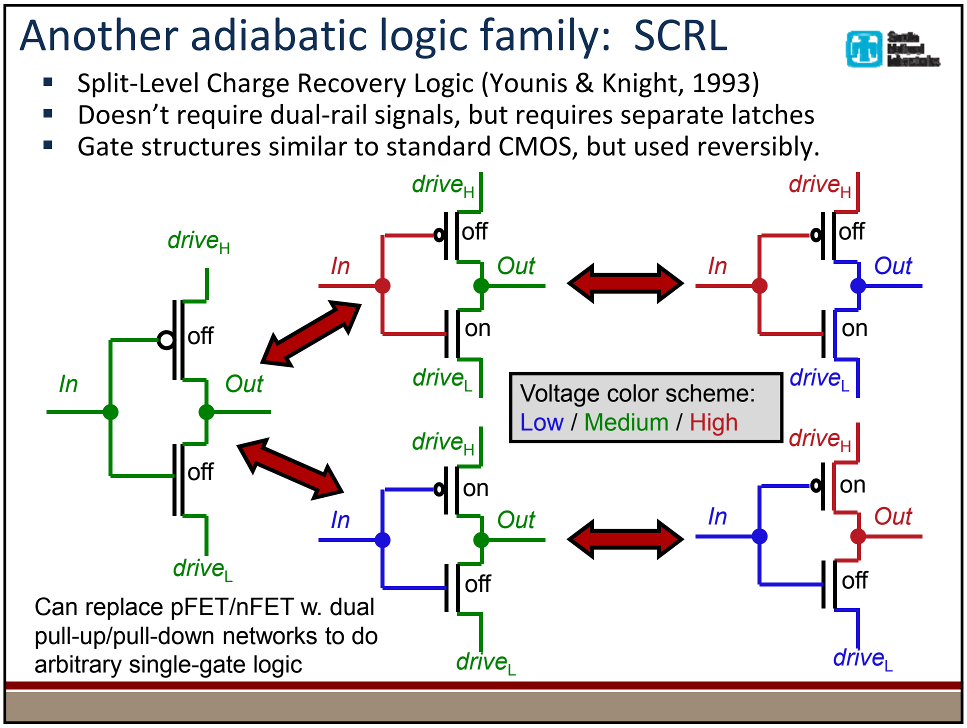


Two-Level Adiabatic Logic (2LAL)

Invented at the University of Florida, circa 2000

- Uses CMOS transmission gates for full-swing switching
  - Logic signals implicitly dual-rail (complementary PN pairs)
  - Logic NOT can be done by simply swapping (relabeling) rails
- Series/parallel T-gate combinations can do Boolean logic…
  - The parallel gate pair at right can be used to (conditionally) reversibly compute the output Q as $A \vee B$ (logic OR)
  - By DeMorgan's law, by complementing both inputs and output of this structure, we also get: $Q = \overline{\overline{A} \vee \overline{B}} = A \wedge B$ (logic AND).
  - By cascading such gates, we can compute any binary function.
- Operation sequence:
  1. Precondition: Output signal Q is initially at logic 0
  2. Driving signal D is also initially logic 0
  3. At time 1 (@1), inputs A, B transition to new levels
     - Connecting D to Q if and only if A or B is logic 1
  4. At time 2 (@2), driver D transitions from 0 to 1
     - Q follows it to 1 if and only if A or B is logic 1
     - Now Q is the logical OR of inputs A,B
- Additional reversible steps that we can do afterwards:
  - Restore A, B to 0 (latches output Q in place at its current level)
    - 2LAL was the first adiabatic logic family capable of doing both logic and latching in the same structure!
  - Or, simply perform the above operation sequence in reverse

(and similarly for Q_P)



Another adiabatic logic family: SCRL

- Split-Level Charge Recovery Logic (Younis & Knight, 1993)
- Doesn't require dual-rail signals, but requires separate latches
- Gate structures similar to standard CMOS, but used reversibly.

Voltage color scheme:
Low / Medium / High

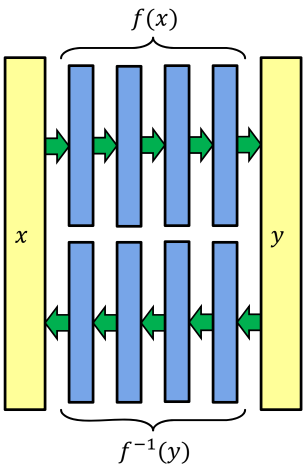
Can replace pFET/nFET w. dual pull-up/pull-down networks to do arbitrary single-gate logic

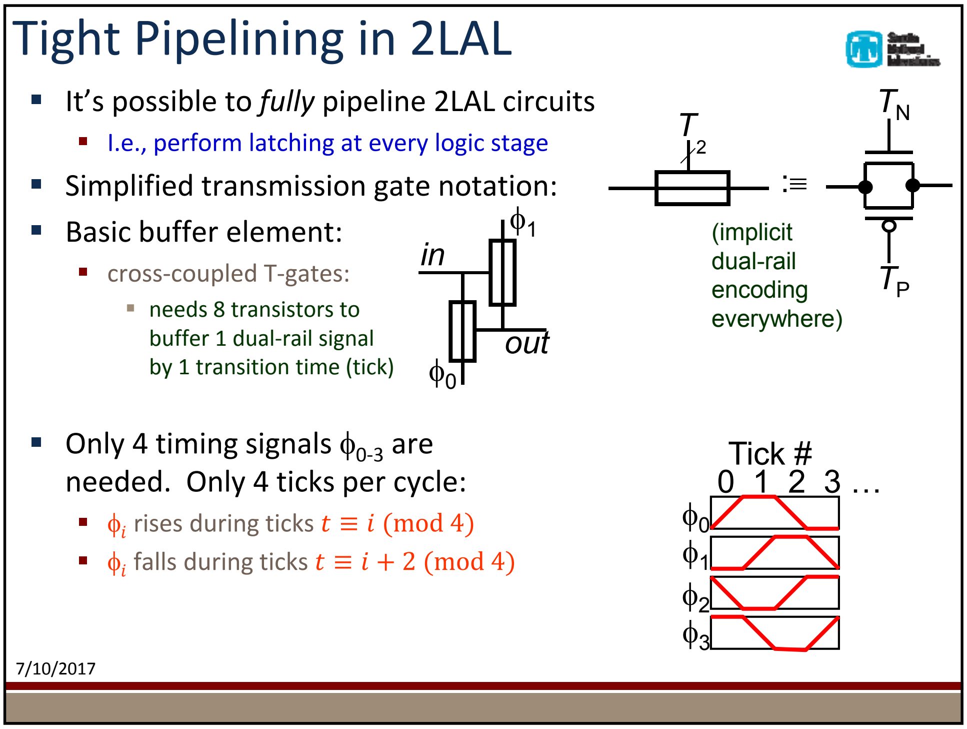
Dynamic vs. Static Latching

- Generally speaking, there are two ways data can be latched (stored) in a CMOS circuit:
  - Dynamic latching: Data is preserved capacitively on a “floating” node
    - Disadvantage: Data can be invalidated by leakage
  - Static latching: Data is preserved by a persistent connection to a voltage reference
    - This tends to be essential to store data long-term without refreshing
      - Particularly useful in adiabatic circuits to prevent $\frac{1}{2}CV_{\mathrm{drift}}^2$ energy loss on refresh
    - Disadvantage: Typically requires extra circuit complexity to implement.
- The same dichotomy applies in adiabatic circuits
  - Note: Leakage still results in extra power dissipation regardless
- To implement static latching in adiabatic circuits:
  - Make sure node is connected to at least one voltage source at all times
    - This may require taking additional steps (we’ll see an example later)

Combinational and Sequential Logic in Reversible Adiabatic Circuits

- A general picture of how to combine combinational and sequential logic in reversible, adiabatic logic designs:
  1. Initially, input x is in register at left.
  2. Evaluate top stages, in sequence, to produce output $y = f(x)$ in register at right.
     - Hall’s “retractile cascade” method
  3. Latch output y in place.
  4. Unroll evaluation of top stages.
- If f is an invertible function, we can then *decompute* the input x as follows:
  5. Evaluate bottom stages, following arrows, to compute a copy of $x = f^{-1}(y)$,
  6. Unlatch (connect) x to the presented copy,
  7. Unroll evaluation of bottom stages.
- At conclusion of this process, information has moved and transformed from x to y.
  - Can then go through further stages, and meanwhile process new inputs (pipelining)…





Tight Pipelining in 2LAL

- It's possible to *fully* pipeline 2LAL circuits
  - I.e., perform latching at every logic stage
- Simplified transmission gate notation:
- Basic buffer element:
  - cross-coupled T-gates:
    - needs 8 transistors to buffer 1 dual-rail signal by 1 transition time (tick)

(implicit dual-rail encoding everywhere)

- Only 4 timing signals $\phi_{0\text{-}3}$ are needed. Only 4 ticks per cycle:
  - ϕ_i rises during ticks $t \equiv i \pmod 4$
  - ϕ_i falls during ticks $t \equiv i + 2 \pmod 4$

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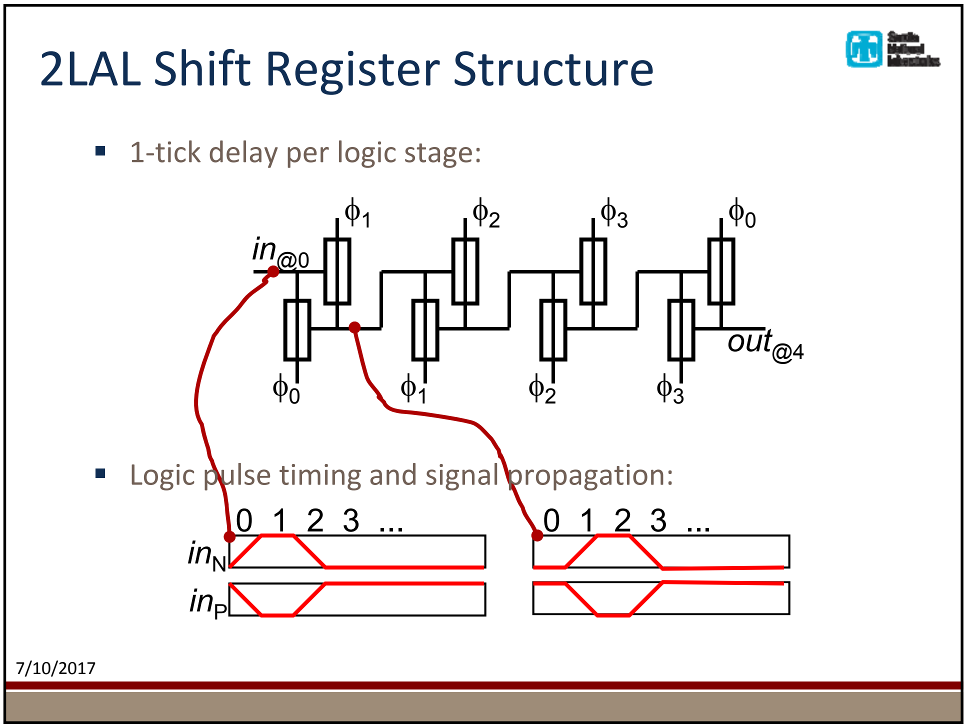

2LAL Shift Register Structure

- 1-tick delay per logic stage:
- Logic pulse timing and signal propagation:

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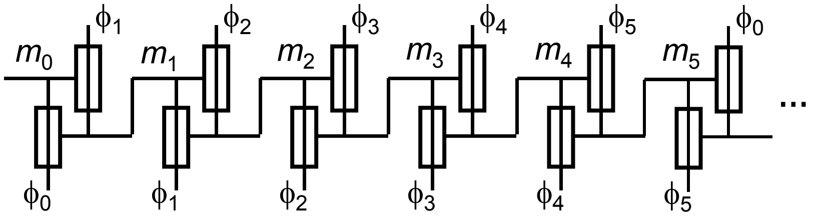
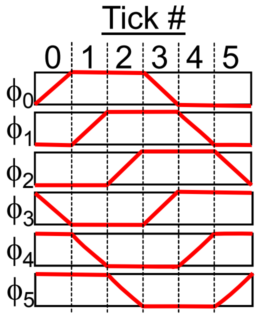
Statically-Latched 2LAL Shift Register

The previous circuit used dynamic latching, but we can also latch statically in 2LAL…



Six timing signals $\phi_{0\text{-}5}$ are needed in this case.
Need six ticks per cycle:

- ϕ_i rises during ticks $t \equiv i \pmod 6$
- ϕ_i falls during ticks $t \equiv i + 3 \pmod 6$



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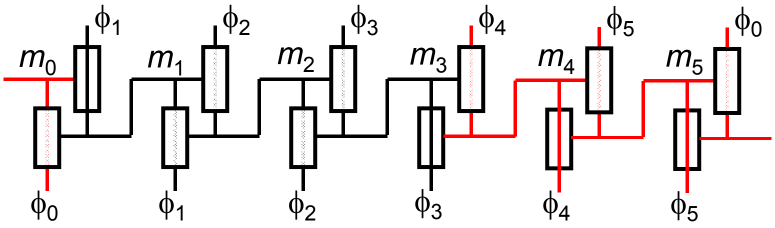
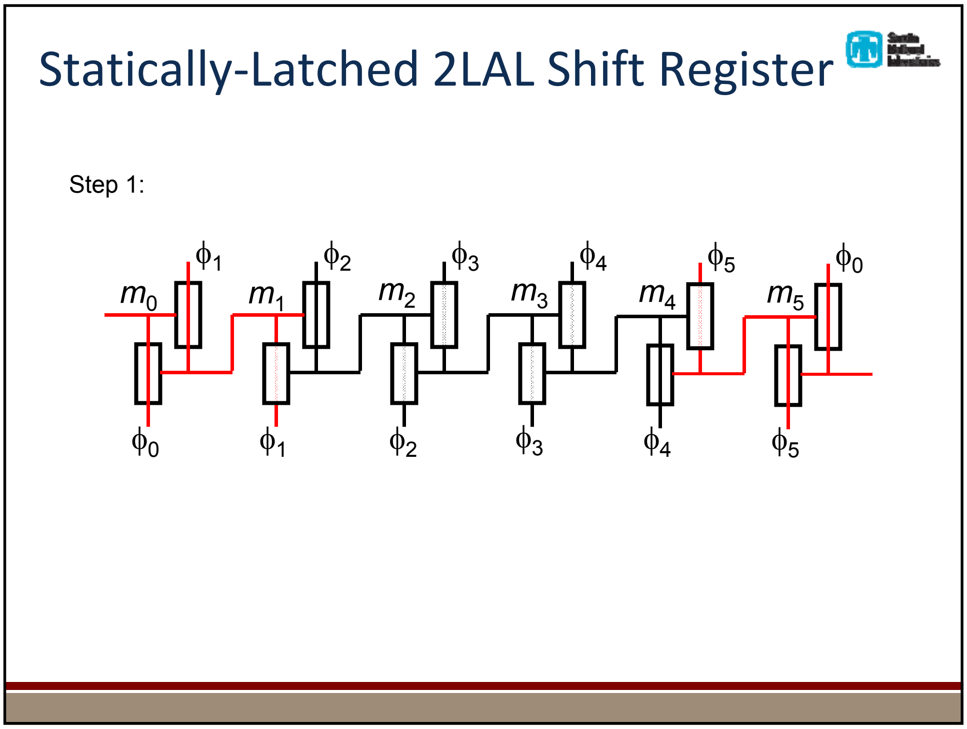
Statically-Latched 2LAL Shift Register

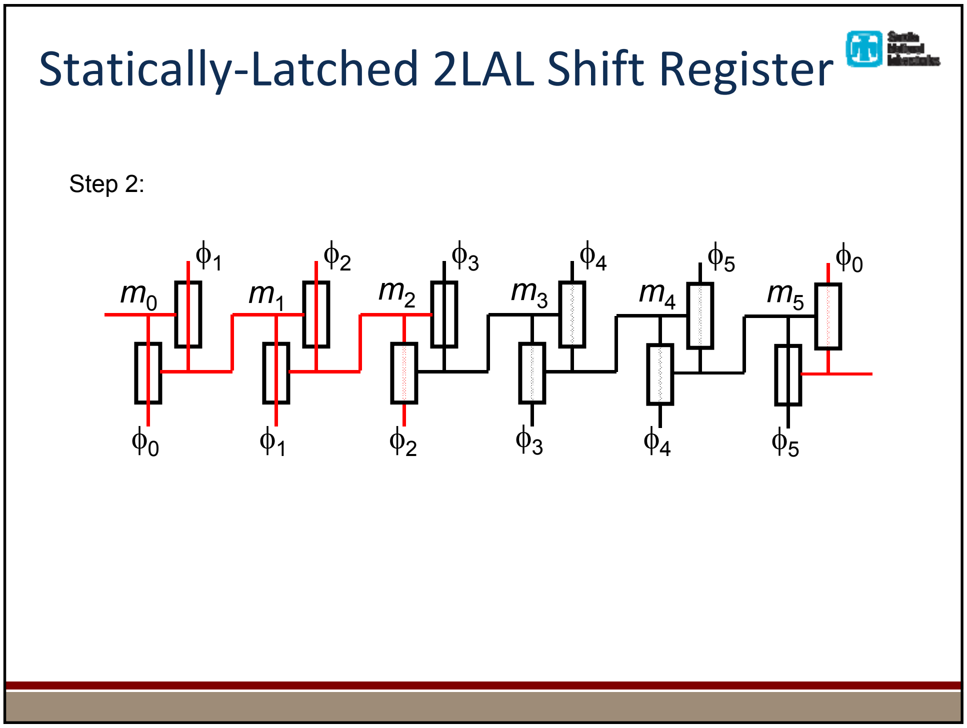
Step 0:





Statically-Latched 2LAL Shift Register

Step 1:

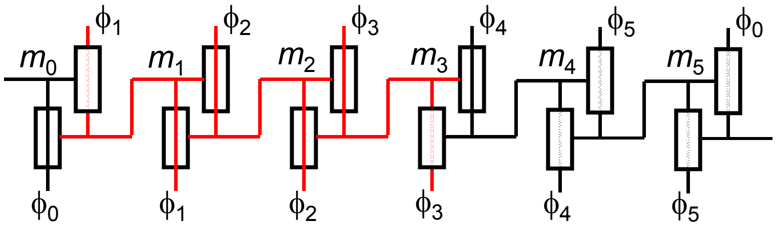


Statically-Latched 2LAL Shift Register

Step 2:

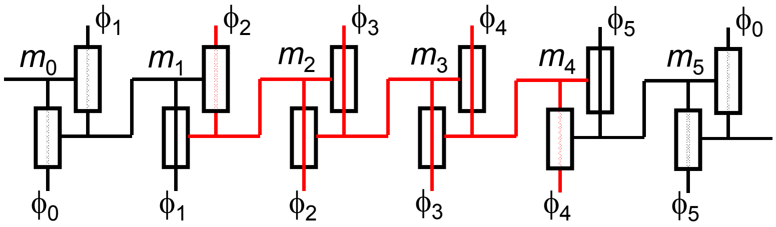
Statically-Latched 2LAL Shift Register

Step 3:



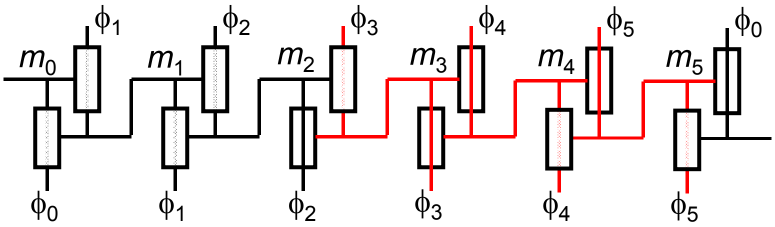
Statically-Latched 2LAL Shift Register

Step 4:



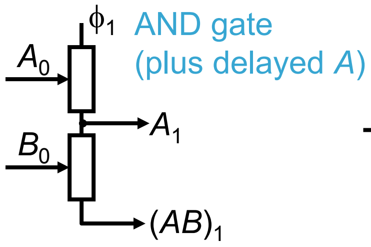
Statically-Latched 2LAL Shift Register

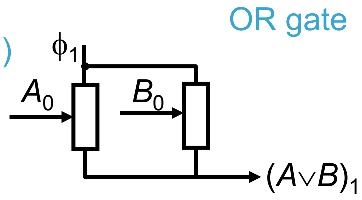
Step 5:



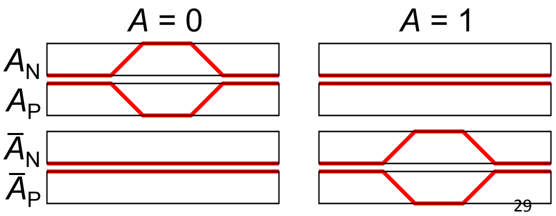
More Complex Logic Functions

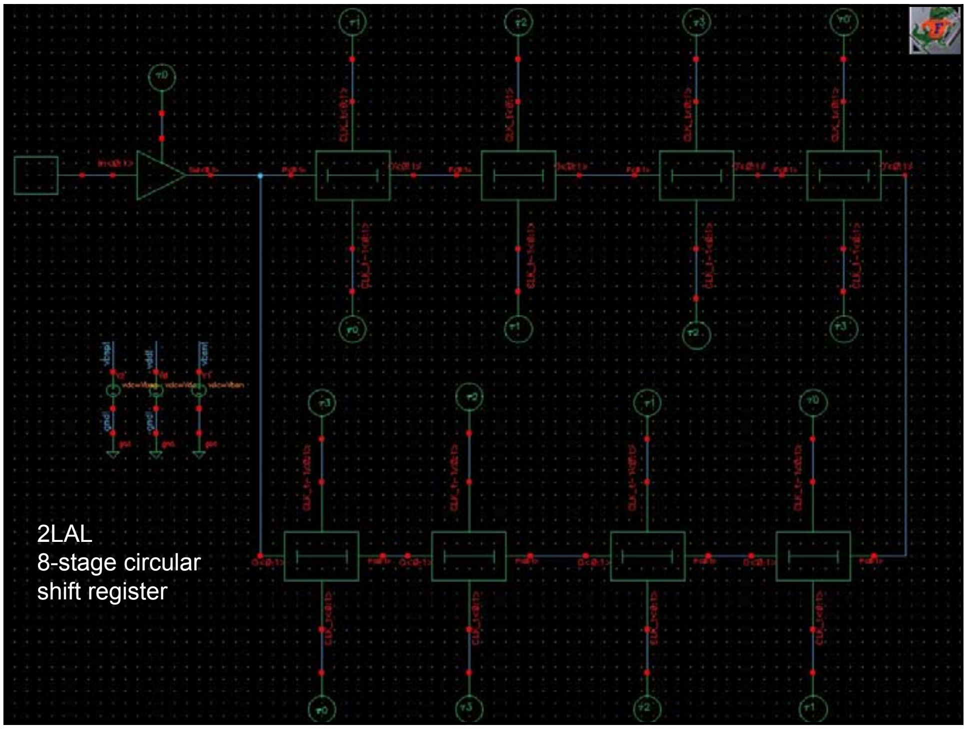
- Non-inverting multi-input Boolean functions:





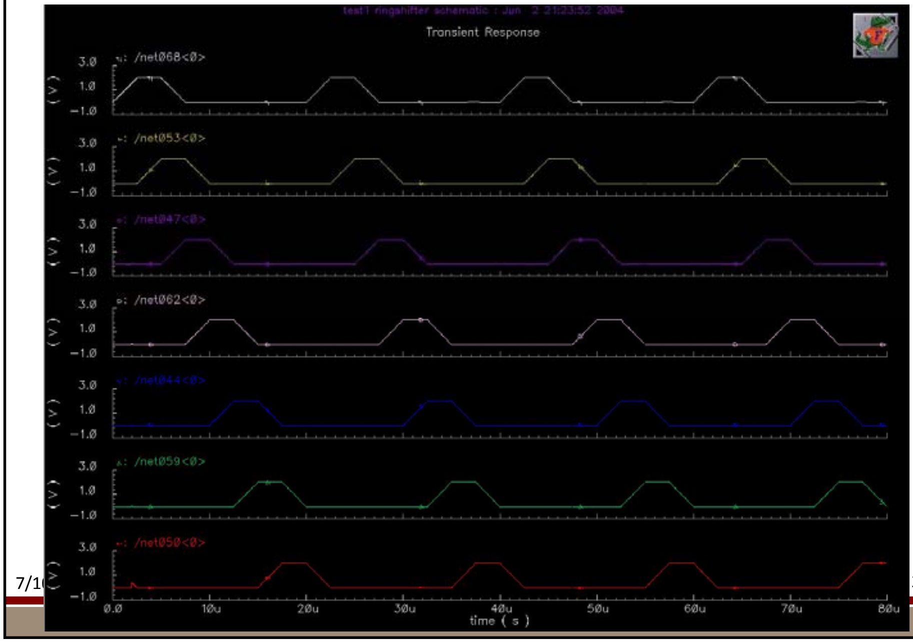
- One way to do inverting functions in fully-pipelined latching logic is to use a quad-rail logic encoding:
  - To invert, swap the complementary pairs
    - Zero-transistor “inverters.”

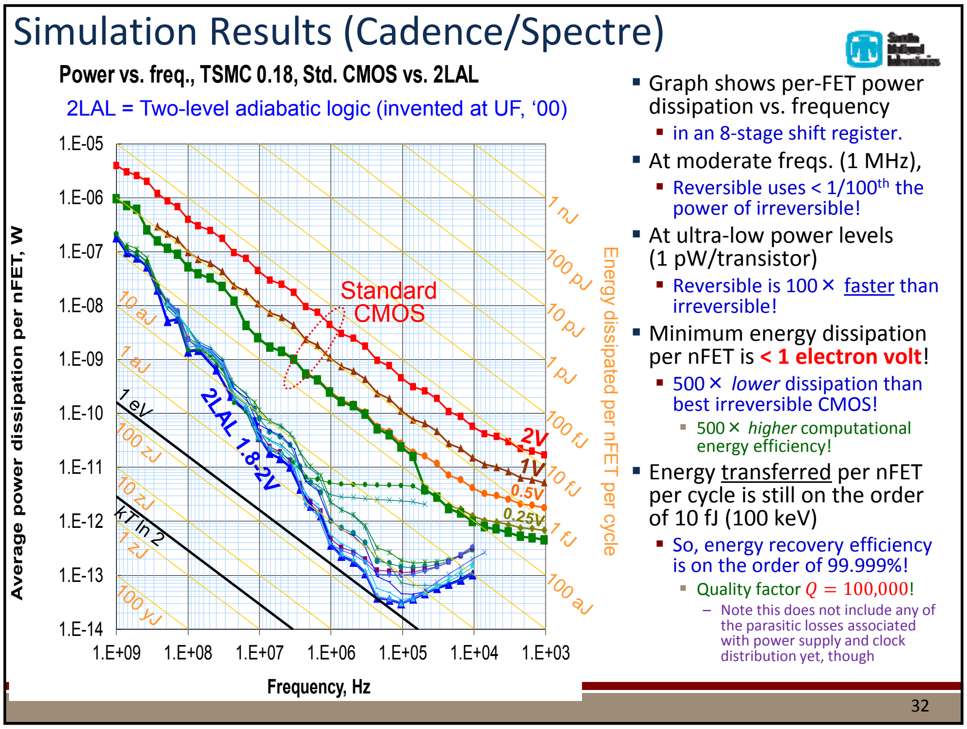




2LAL
8-stage circular
shift register

Pulse propagation in 8-stage circuit



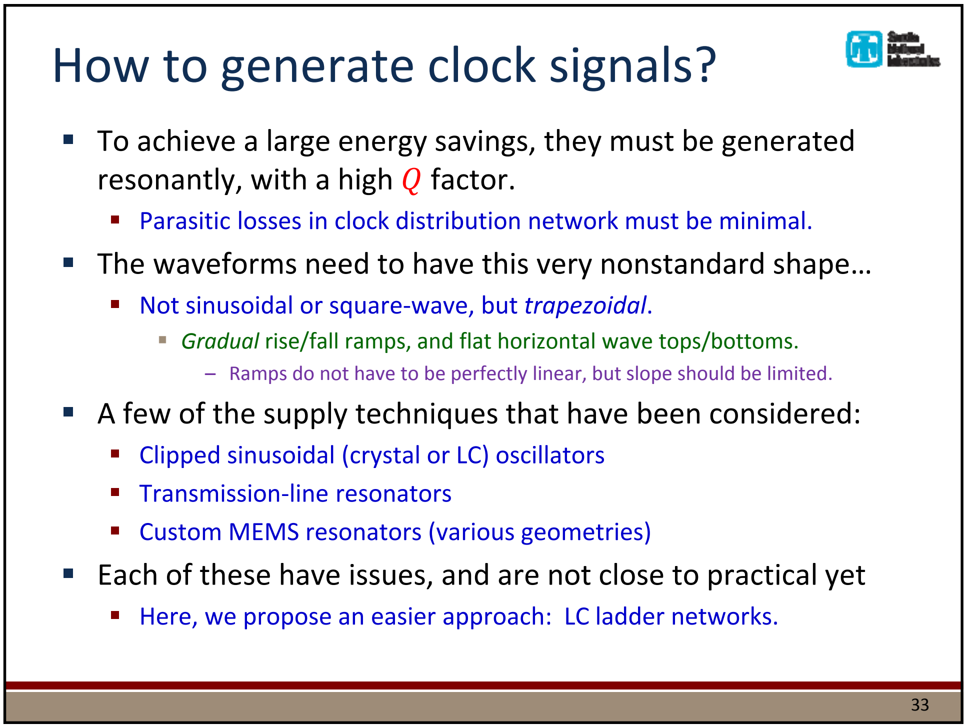


Simulation Results (Cadence/Spectre)

Power vs. freq., TSMC 0.18, Std. CMOS vs. 2LAL

2LAL = Two-level adiabatic logic (invented at UF, '00)

- Graph shows per-FET power dissipation vs. frequency
  - in an 8-stage shift register.
- At moderate freqs. (1 MHz),
  - Reversible uses < 1/100th the power of irreversible!
- At ultra-low power levels (1 pW/transistor)
  - Reversible is 100 × faster than irreversible!
- Minimum energy dissipation per nFET is **< 1 electron volt**!
  - 500 × *lower* dissipation than best irreversible CMOS!
    - 500 × *higher* computational energy efficiency!
- Energy transferred per nFET per cycle is still on the order of 10 fJ (100 keV)
  - So, energy recovery efficiency is on the order of 99.999%!
    - Quality factor $Q = 100{,}000$!
      - Note this does not include any of the parasitic losses associated with power supply and clock distribution yet, though



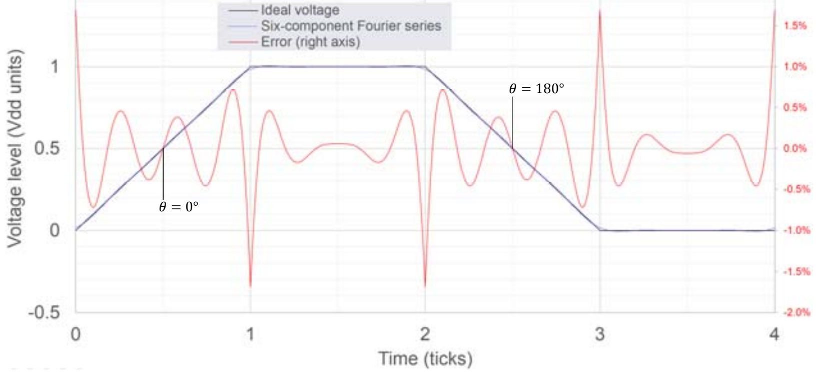
How to generate clock signals?

- To achieve a large energy savings, they must be generated resonantly, with a high Q factor.
  - Parasitic losses in clock distribution network must be minimal.
- The waveforms need to have this very nonstandard shape…
  - Not sinusoidal or square-wave, but *trapezoidal*.
    - *Gradual* rise/fall ramps, and flat horizontal wave tops/bottoms.
      - Ramps do not have to be perfectly linear, but slope should be limited.
- A few of the supply techniques that have been considered:
  - Clipped sinusoidal (crystal or LC) oscillators
  - Transmission-line resonators
  - Custom MEMS resonators (various geometries)
- Each of these have issues, and are not close to practical yet
  - Here, we propose an easier approach: LC ladder networks.

Spectrum of Trapezoidal Wave

- Relative to mid-level crossing, waveform is an odd function
  - Spectrum includes only odd harmonics $f, 3f, 5f, \ldots$
- Six-component Fourier series expansion is shown below
  - Maximum offset with $11f$ frequency cutoff is $< 1.7\%$ of V_{dd}

$$v_{f6}(t) = V_{dd}\left[\frac{1}{2} + \frac{4\sqrt{2}}{\pi^2}\left(\sin\theta + \frac{\sin 3\theta}{3^2} - \frac{\sin 5\theta}{5^2} - \frac{\sin 7\theta}{7^2} + \frac{\sin 9\theta}{9^2} + \frac{\sin 11\theta}{11^2}\right)\right]$$



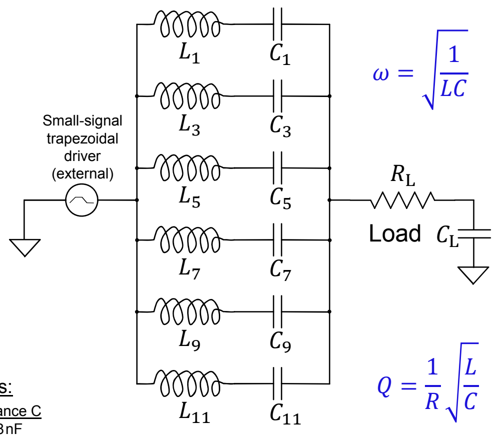
Ladder Resonator Structure

- Can build trapezoidal resonator w. a ladder circuit made of parallel passive bandpass filters, each a sinusoidal LC resonator
  - Each "rung" of ladder passes a different odd multiple of the fundamental clock frequency f
  - Adjust L/C ratio to obtain a target Q value on each path, given parasitic R, C values
- Excite the circuit with a driving signal containing the right distribution of frequency component amplitudes
  - Each frequency component gets amplified by the Q value of its corresponding rung
  - If all rungs are designed to the same target Q, we can just use a trapezoidal driver
- For high Q, clock period must be long compared to the total parasitic RC…
  - Max. possible $Q_n = \frac{1}{2\pi} \cdot \frac{t_{\mathrm{period},n}}{(RC)_{\mathrm{parasitic}}}$

(for $V_{\mathrm{dd}} \approx 1.75\ \mathrm{V}\ \downarrow$)

Example values:

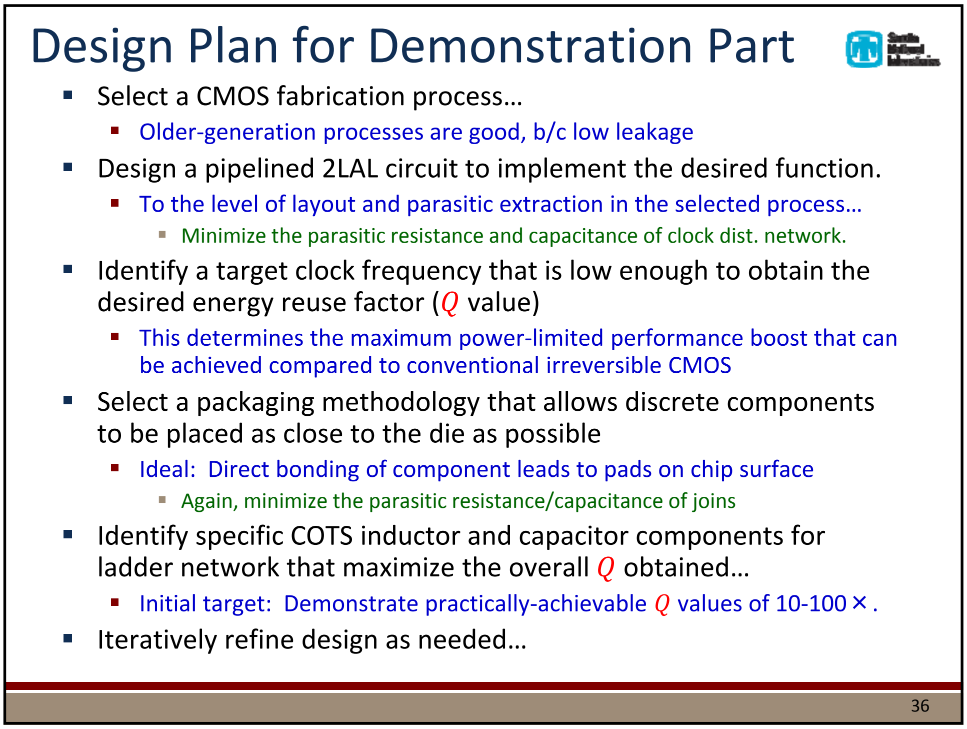
harmonic mode (n)	frequency f	component amplitude Va	inductance L	capacitance C
1	230 kHz	1000.00 mV	691.98 nH	691.98 nF
3	690 kHz	111.11 mV	230.66 nH	230.66 nF
5	1150 kHz	-40.00 mV	138.40 nH	138.40 nF
7	1610 kHz	-20.41 mV	98.85 nH	98.85 nF
9	2070 kHz	12.35 mV	76.89 nH	76.89 nF
11	2530 kHz	8.26 mV	62.91 nH	62.91 nF



$$\omega = \sqrt{\frac{1}{LC}}$$

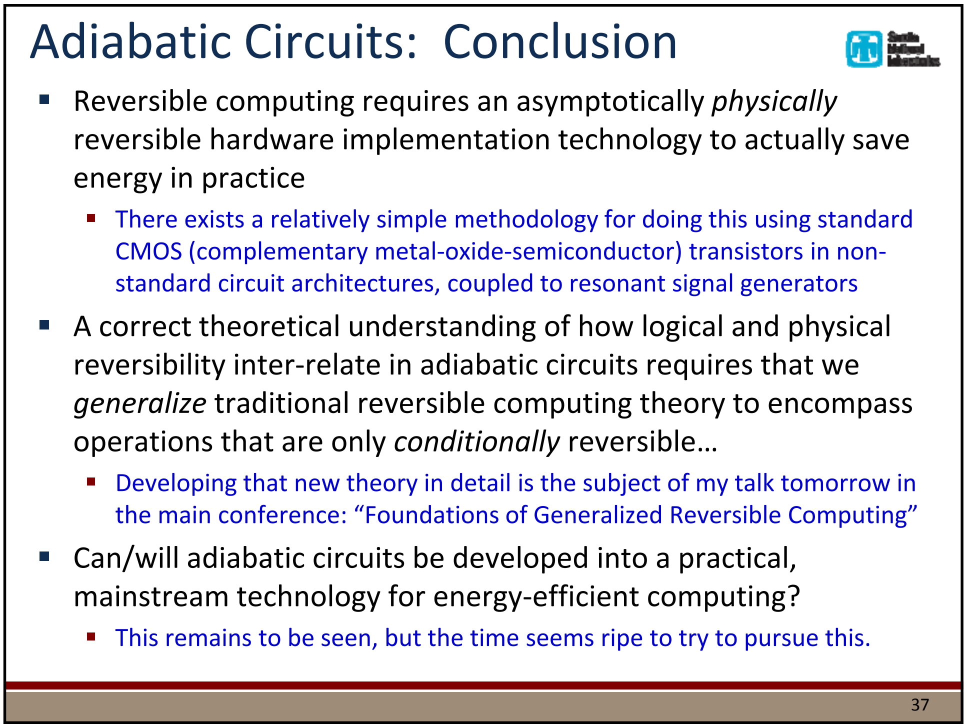
$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Ladder Resonator for Odd Harmonics



Design Plan for Demonstration Part

- Select a CMOS fabrication process…
  - Older-generation processes are good, b/c low leakage
- Design a pipelined 2LAL circuit to implement the desired function.
  - To the level of layout and parasitic extraction in the selected process…
    - Minimize the parasitic resistance and capacitance of clock dist. network.
- Identify a target clock frequency that is low enough to obtain the desired energy reuse factor (Q value)
  - This determines the maximum power-limited performance boost that can be achieved compared to conventional irreversible CMOS
- Select a packaging methodology that allows discrete components to be placed as close to the die as possible
  - Ideal: Direct bonding of component leads to pads on chip surface
    - Again, minimize the parasitic resistance/capacitance of joins
- Identify specific COTS inductor and capacitor components for ladder network that maximize the overall Q obtained…
  - Initial target: Demonstrate practically-achievable Q values of 10-100×.
- Iteratively refine design as needed…



Adiabatic Circuits: Conclusion

- Reversible computing requires an asymptotically *physically* reversible hardware implementation technology to actually save energy in practice
  - There exists a relatively simple methodology for doing this using standard CMOS (complementary metal-oxide-semiconductor) transistors in non-standard circuit architectures, coupled to resonant signal generators
- A correct theoretical understanding of how logical and physical reversibility inter-relate in adiabatic circuits requires that we *generalize* traditional reversible computing theory to encompass operations that are only *conditionally* reversible…
  - Developing that new theory in detail is the subject of my talk tomorrow in the main conference: "Foundations of Generalized Reversible Computing"
- Can/will adiabatic circuits be developed into a practical, mainstream technology for energy-efficient computing?
  - This remains to be seen, but the time seems ripe to try to pursue this.