Introduction to CMOS VLSI Design

Lecture 16: Circuit Pitfalls

David Harris

Harvey Mudd College

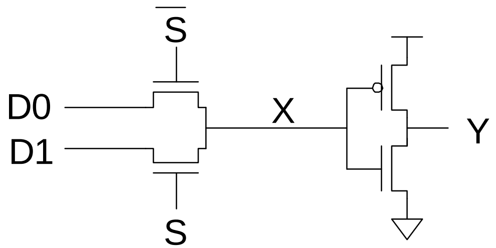
Spring 2004

Outline

- Circuit Pitfalls
  - Detective puzzle
  - Given circuit and symptom, diagnose cause and recommend solution
  - All these pitfalls have caused failures in real chips
- Noise Budgets
- Reliability

Bad Circuit 1

- Circuit
  - 2:1 multiplexer



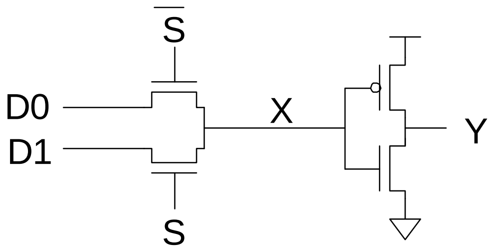
- Principle:

- Solution:

- Symptom
  - Mux works when selected D is 0 but not 1.
  - Or fails at low V_{DD}.
  - Or fails in SFSF corner.

Bad Circuit 1

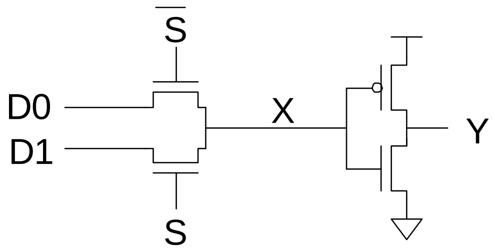
- Circuit
  - 2:1 multiplexer



- Symptom
  - Mux works when selected D is 0 but not 1.
  - Or fails at low V_{DD}.
  - Or fails in SFSF corner.
- Principle: Threshold drop
  - X never rises above V_{DD}-V_t
  - V_t is raised by the body effect
  - The threshold drop is most serious as V_t becomes a greater fraction of V_{DD}.
- Solution:

Bad Circuit 1

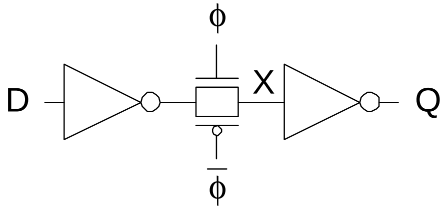
- Circuit
  - 2:1 multiplexer



- Symptom
  - Mux works when selected D is 0 but not 1.
  - Or fails at low V_{DD}.
  - Or fails in SFSF corner.
- Principle: Threshold drop
  - X never rises above V_{DD}-V_t
  - V_t is raised by the body effect
  - The threshold drop is most serious as V_t becomes a greater fraction of V_{DD}.
- Solution: Use transmission gates, not pass transistors

Bad Circuit 2

- Circuit
  - Latch

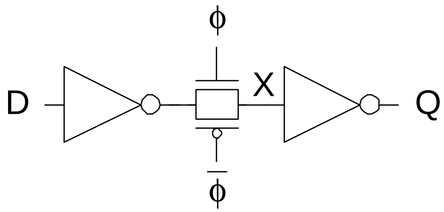


- Principle:
- Solution:

- Symptom
  - Load a 0 into Q
  - Set ϕ = 0
  - Eventually Q spontaneously flips to 1

Bad Circuit 2

- Circuit
  - Latch

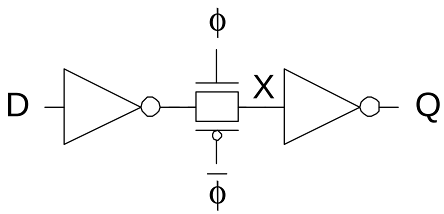


- Symptom
  - Load a 0 into Q
  - Set $\phi = 0$
  - Eventually Q spontaneously flips to 1

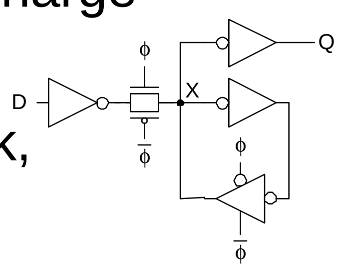
- Principle: Leakage
  - X is a dynamic node holding value as charge on the node
  - Eventually subthreshold leakage may disturb charge
- Solution:

Bad Circuit 2

- Circuit
  - Latch

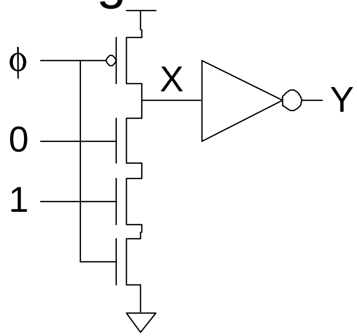


- Symptom
  - Load a 0 into Q
  - Set $\phi = 0$
  - Eventually Q spontaneously flips to 1
- Principle: Leakage
  - X is a dynamic node holding value as charge on the node
  - Eventually subthreshold leakage may disturb charge
- Solution: Staticize node with feedback
  - Or periodically refresh node (requires fast clock, not practical processes with big leakage)



Bad Circuit 3

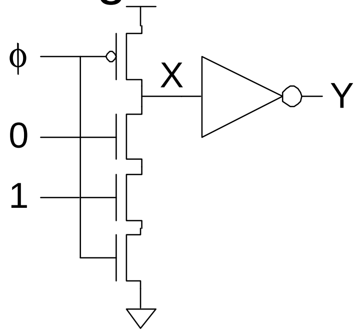
- Circuit
  - Domino AND gate



- Symptom
  - Precharge gate (Y=0)
  - Then evaluate
  - Eventually Y spontaneously flips to 1
- Principle:
- Solution:

Bad Circuit 3

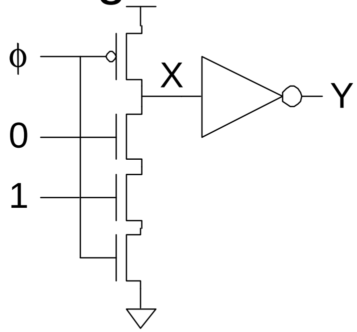
- Circuit
  - Domino AND gate



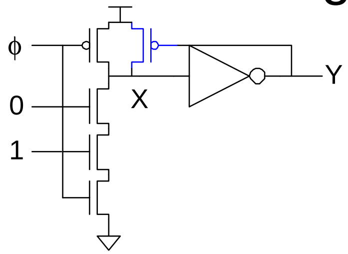
- Symptom
  - Precharge gate (Y=0)
  - Then evaluate
  - Eventually Y spontaneously flips to 1
- Principle: Leakage
  - X is a dynamic node holding value as charge on the node
  - Eventually subthreshold leakage may disturb charge
- Solution:

Bad Circuit 3

- Circuit
  - Domino AND gate

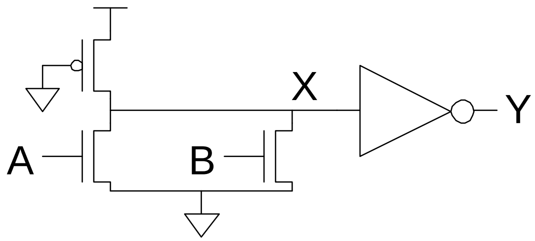


- Symptom
  - Precharge gate (Y=0)
  - Then evaluate
  - Eventually Y spontaneously flips to 1
- Principle: Leakage
  - X is a dynamic node holding value as charge on the node
  - Eventually subthreshold leakage may disturb charge
- Solution: Keeper



Bad Circuit 4

- Circuit
  - Pseudo-nMOS OR



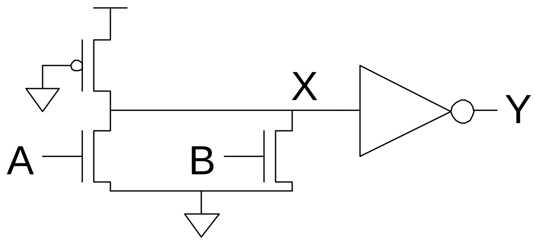
- Principle:

- Solution:

- Symptom
  - When only one input is true, Y = 0.
  - Perhaps only happens in SF corner.

Bad Circuit 4

- Circuit
  - Pseudo-nMOS OR

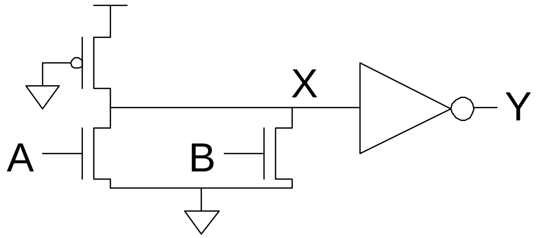


- Symptom
  - When only one input is true, Y = 0.
  - Perhaps only happens in SF corner.

- Principle: Ratio Failure
  - nMOS and pMOS fight each other.
  - If the pMOS is too strong, nMOS cannot pull X low enough.
- Solution:

Bad Circuit 4

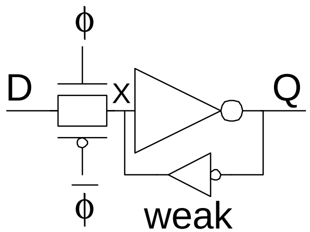
- Circuit
  - Pseudo-nMOS OR



- Symptom
  - When only one input is true, Y = 0.
  - Perhaps only happens in SF corner.
- Principle: Ratio Failure
  - nMOS and pMOS fight each other.
  - If the pMOS is too strong, nMOS cannot pull X low enough.
- Solution: Check that ratio is satisfied in all corners

Bad Circuit 5

- Circuit
  - Latch



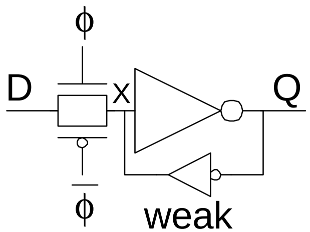
- Principle:

- Solutions:

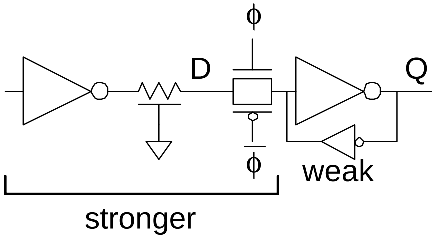
- Symptom
  - Q stuck at 1.
  - May only happen for certain latches where input is driven by a small gate located far away.

Bad Circuit 5

- Circuit
  - Latch



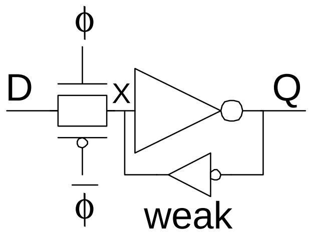
- Symptom
  - Q stuck at 1.
  - May only happen for certain latches where input is driven by a small gate located far away.
- Principle: Ratio Failure (again)
  - Series resistance of D driver, wire resistance, and tgate must be much less than weak feedback inverter.



- Solutions:

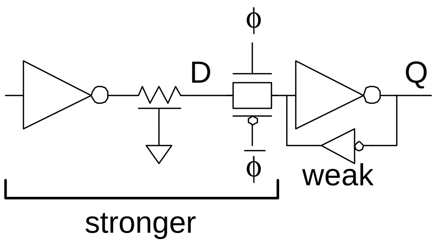
Bad Circuit 5

- Circuit
  - Latch



- Symptom
  - Q stuck at 1.
  - May only happen for certain latches where input is driven by a small gate located far away.

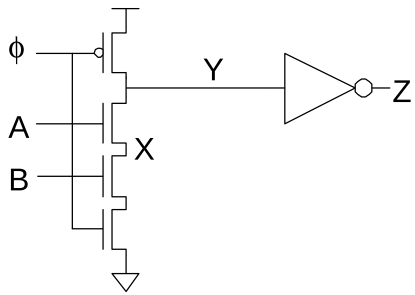
- Principle: Ratio Failure (again)
  - Series resistance of D driver, wire resistance, and tgate must be much less than weak feedback inverter.



- Solutions: Check relative strengths
  - Avoid unbuffered diffusion inputs where driver is unknown

Bad Circuit 6

- Circuit
  - Domino AND gate



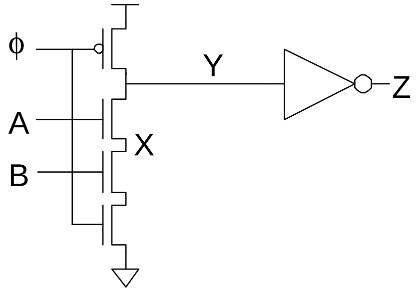
- Principle:

- Solutions:

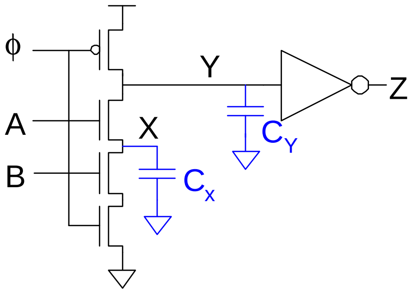
- Symptom
  - Precharge gate while A = B = 0, so Z = 0
  - Set $\phi = 1$
  - A rises
  - Z is observed to sometimes rise

Bad Circuit 6

- Circuit
  - Domino AND gate

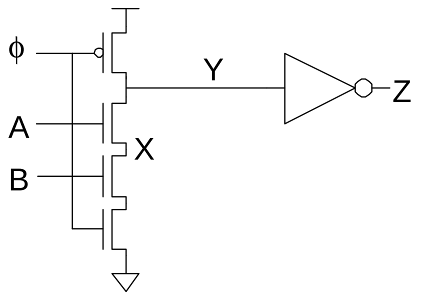


- Symptom
  - Precharge gate while A = B = 0, so Z = 0
  - Set ϕ = 1
  - A rises
  - Z is observed to sometimes rise
- Principle: Charge Sharing
  - If X was low, it shares charge with Y
- Solutions:



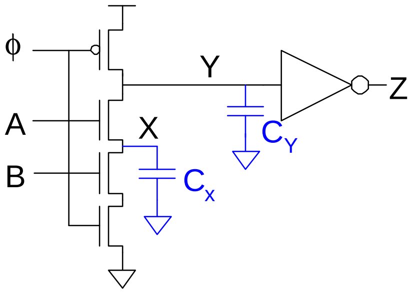
Bad Circuit 6

- Circuit
  - Domino AND gate



- Symptom
  - Precharge gate while $A = B = 0$, so $Z = 0$
  - Set $\phi = 1$
  - A rises
  - Z is observed to sometimes rise

- Principle: Charge Sharing
  - If X was low, it shares charge with Y



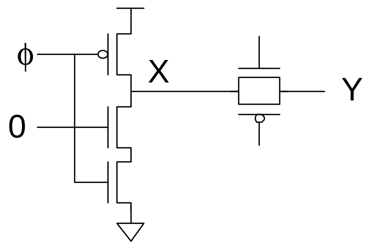
- Solutions: Limit charge sharing

$$V_x = V_Y = \frac{C_Y}{C_x + C_Y} V_{DD}$$

  - Safe if $C_Y >> C_X$
  - Or precharge node X too

Bad Circuit 7

- Circuit
  - Dynamic gate + latch

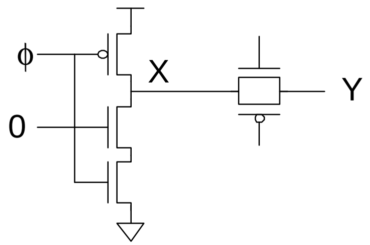


- Principle:
- Solution:

- Symptom
  - Precharge gate while transmission gate latch is opaque
  - Evaluate
  - When latch becomes transparent, X falls

Bad Circuit 7

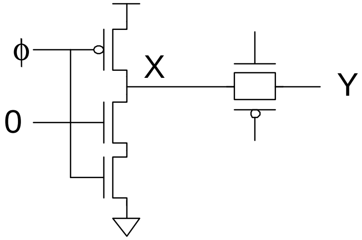
- Circuit
  - Dynamic gate + latch



- Symptom
  - Precharge gate while transmission gate latch is opaque
  - Evaluate
  - When latch becomes transparent, X falls
- Principle: Charge Sharing
  - If Y was low, it shares charge with X
- Solution:

Bad Circuit 7

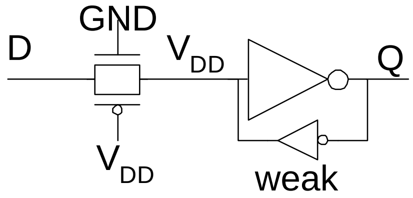
- Circuit
  – Dynamic gate + latch



- Symptom
  – Precharge gate while transmission gate latch is opaque
  – Evaluate
  – When latch becomes transparent, X falls
- Principle: Charge Sharing
  – If Y was low, it shares charge with X
- Solution: Buffer dynamic nodes before driving transmission gate

Bad Circuit 8

- Circuit
  - Latch



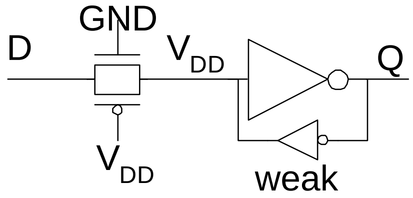
- Principle:

- Solution:

- Symptom
  - Q changes while latch is opaque
  - Especially if D comes from a far-away driver

Bad Circuit 8

- Circuit
  - Latch

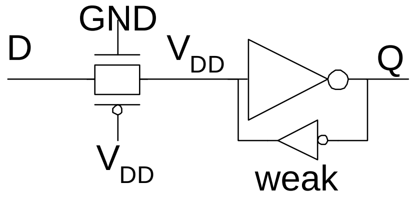


- Symptom
  - Q changes while latch is opaque
  - Especially if D comes from a far-away driver

- Principle: Diffusion Input Noise Sensitivity
  - If D < -V_t, transmission gate turns on
  - Most likely because of power supply noise or coupling on D
- Solution:

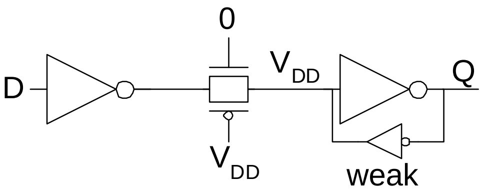
Bad Circuit 8

- Circuit
  - Latch



- Symptom
  - Q changes while latch is opaque
  - Especially if D comes from a far-away driver

- Principle: Diffusion Input Noise Sensitivity
  - If D < -V_t, transmission gate turns on
  - Most likely because of power supply noise or coupling on D
- Solution: Buffer D locally

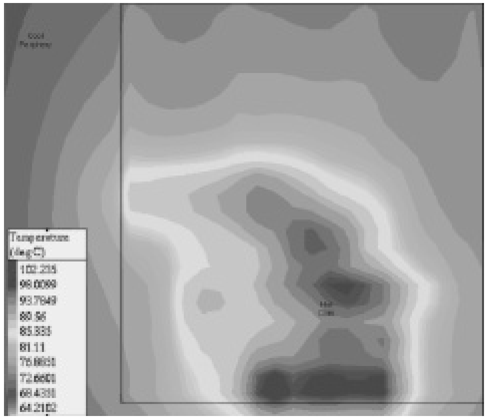


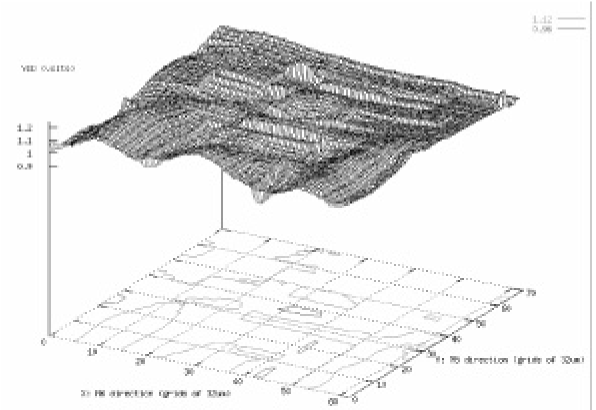
Bad Circuit 9

- Circuit
  - Anything
- Symptom
  - Some gates are slower than expected
- Principle:

Bad Circuit 9

- Circuit
  - Anything
- Symptom
  - Some gates are slower than expected
- Principle: Hot Spots and Power Supply Noise



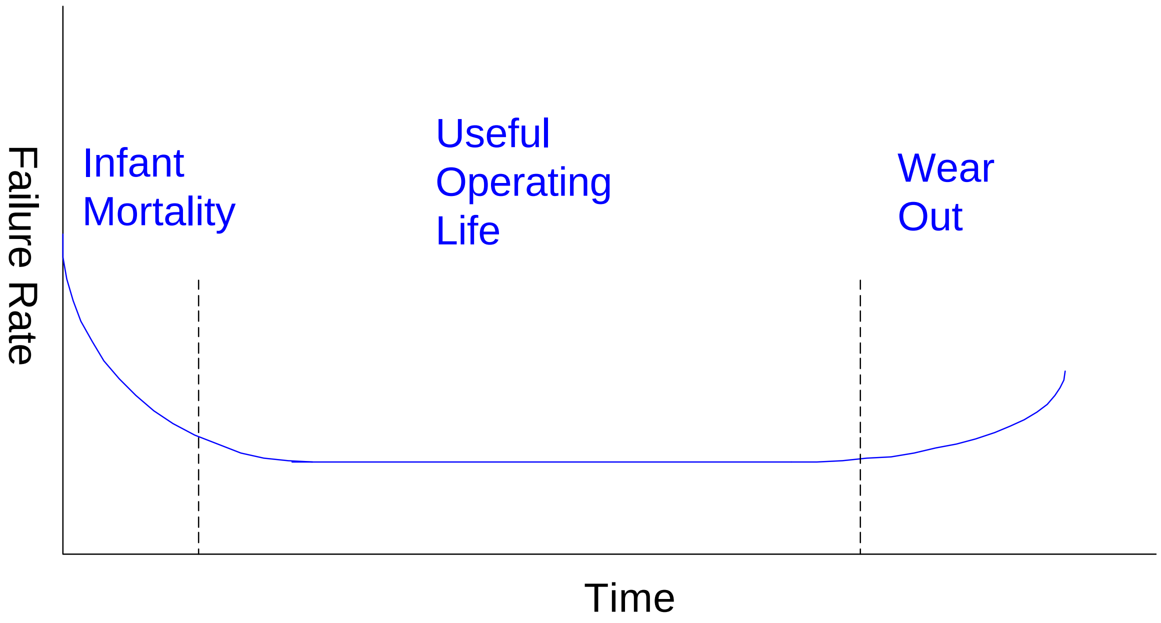


Noise

- Sources
  - Power supply noise / ground bounce
  - Capacitive coupling
  - Charge sharing
  - Leakage
  - Noise feedthrough
- Consequences
  - Increased delay (for noise to settle out)
  - Or incorrect computations

Reliability

- Hard Errors
- Soft Errors



Electromigration

- "Electron wind" causes movement of metal atoms along wires
- Excessive electromigration leads to open circuits
- Most significant for unidirectional (DC) current
  - Depends on current density J_{dc} (current / area)
  - Exponential dependence on temperature
  - Black's Equation: $MTTF \propto \frac{e^{\frac{E_a}{kT}}}{J_{dc}{}^{n}}$
  - Typical limits: $J_{dc} < 1 – 2$ mA / μm^2
- See videos

Self-Heating

- Current through wire resistance generates heat
  - Oxide surrounding wires is a thermal insulator
  - Heat tends to build up in wires
  - Hotter wires are more resistive, slower
- Self-heating limits AC current densities for reliability

$$I_{rms} = \sqrt{\frac{\int_0^T I(t)^2 dt}{T}}$$

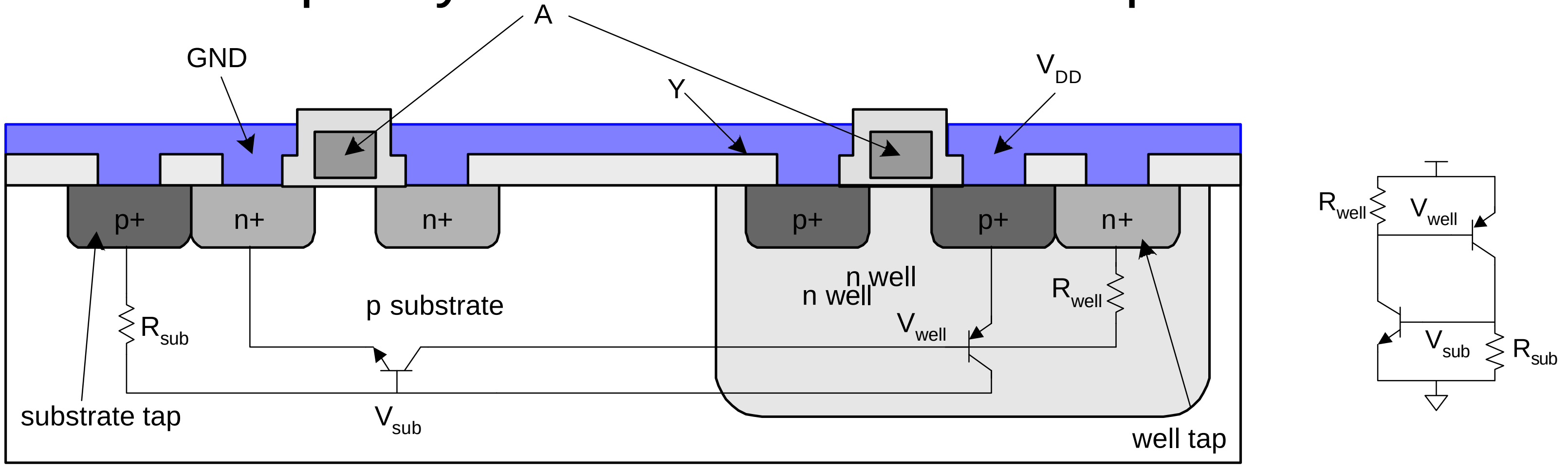
  - Typical limits: $J_{rms} < 15$ mA / μm^2

Hot Carriers

- Electric fields across channel impart high energies to some carriers
  - These "hot" carriers may be blasted into the gate oxide where they become trapped
  - Accumulation of charge in oxide causes shift in V_t over time
  - Eventually V_t shifts too far for devices to operate correctly
- Choose V_{DD} to achieve reasonable product lifetime
  - Worst problems for inverters and NORs with slow input risetime and long propagation delays

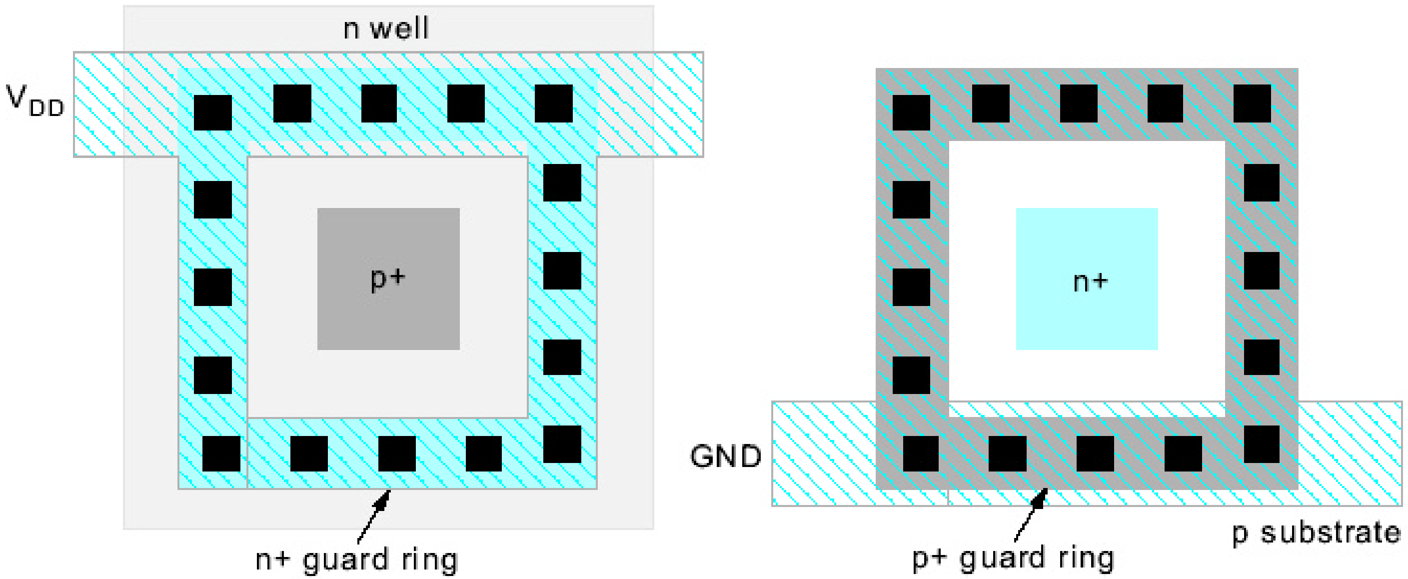
Latchup

- Latchup: positive feedback leading to V_{DD} – GND short
  - Major problem for 1970's CMOS processes before it was well understood
- Avoid by minimizing resistance of body to GND / V_{DD}
  - Use plenty of substrate and well taps



Guard Rings

- Latchup risk greatest when diffusion-to-substrate diodes could become forward-biased
- Surround sensitive region with guard ring to collect injected charge



Overvoltage

- High voltages can damage transistors
  - Electrostatic discharge
  - Oxide arcing
  - Punchthrough
  - Time-dependent dielectric breakdown (TDDB)
    - Accumulated wear from tunneling currents
- Requires low V_{DD} for thin oxides and short channels
- Use ESD protection structures where chip meets real world

Summary

- Static CMOS gates are very robust
  - Will settle to correct value if you wait long enough
- Other circuits suffer from a variety of pitfalls
  - Tradeoff between performance & robustness
- Very important to check circuits for pitfalls
  - For large chips, you need an automatic checker.
  - Design rules aren't worth the paper they are printed on unless you back them up with a tool.

Soft Errors

- In 1970's, DRAMs were observed to occasionally flip bits for no apparent reason
  - Ultimately linked to alpha particles and cosmic rays
- Collisions with particles create electron-hole pairs in substrate
  - These carriers are collected on dynamic nodes, disturbing the voltage
- Minimize soft errors by having plenty of charge on dynamic nodes
- Tolerate errors through ECC, redundancy