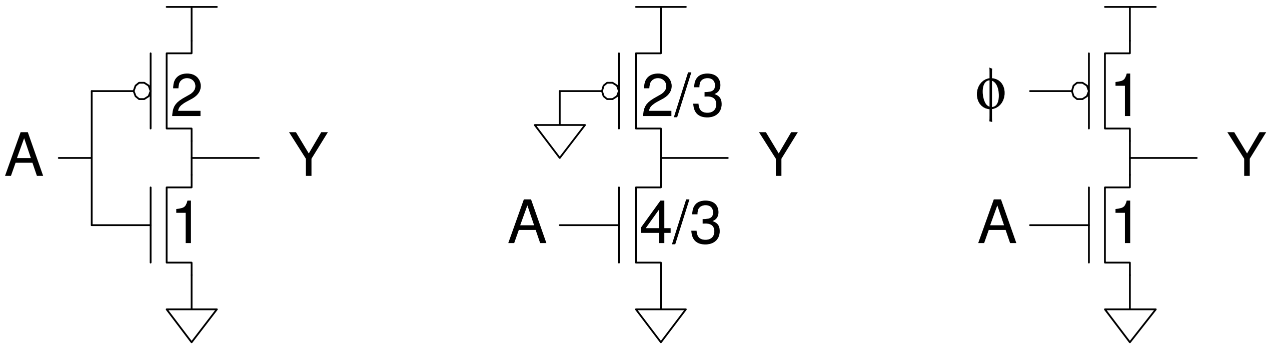
Dynamic Combinational Circuits

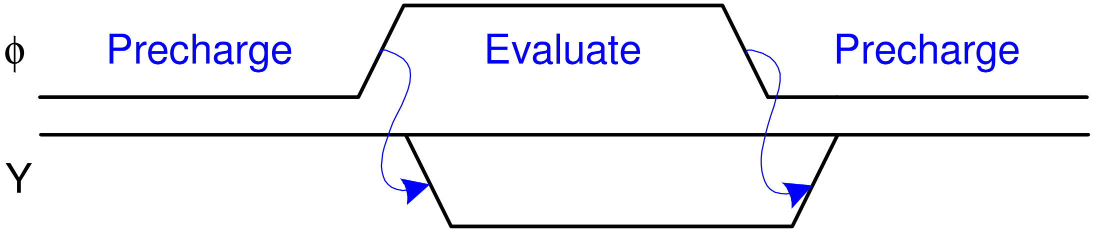
- Dynamic circuits
  - Charge sharing, charge redistribution
- Domino logic
- np-CMOS (zipper CMOS)

Dynamic Logic

- *Dynamic* gates use a clocked pMOS pullup
- Two modes: *precharge* and *evaluate*

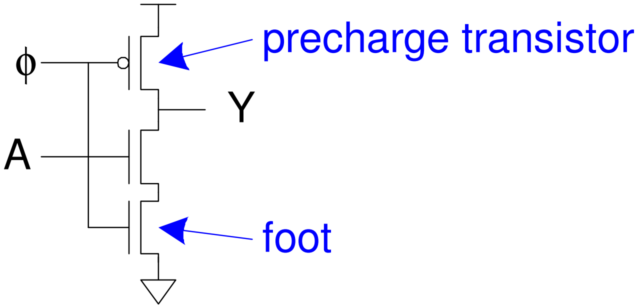


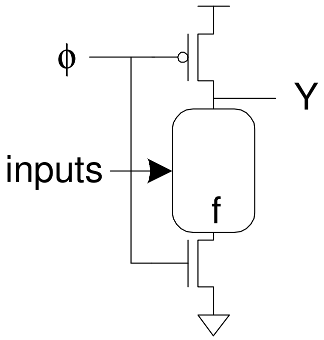
Static Pseudo-nMOS Dynamic



The Foot

- What if pulldown network is ON during precharge?
- Use series evaluation transistor to prevent fight.





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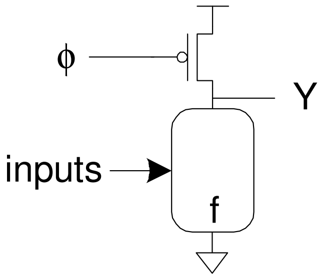
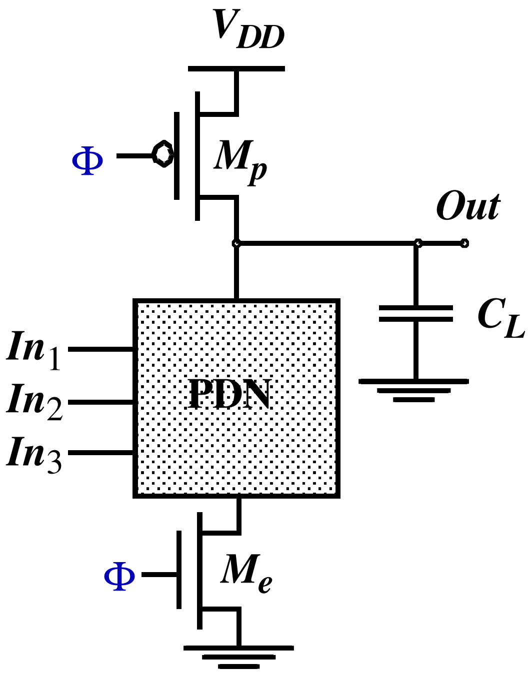
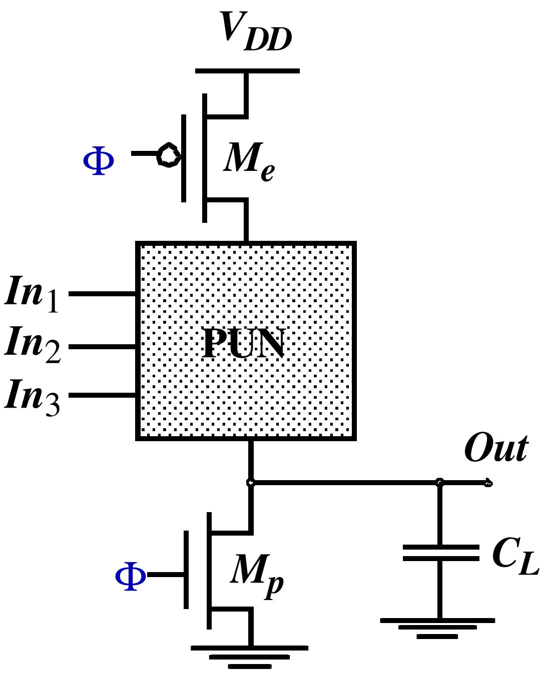


unfooted

Dynamic Logic



Φn network

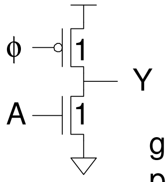
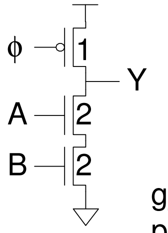
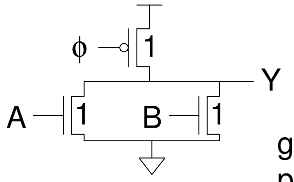
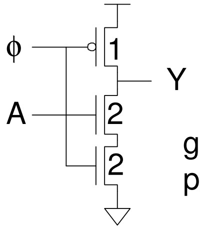
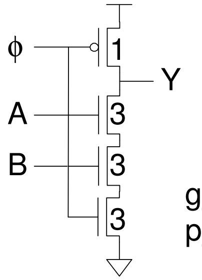
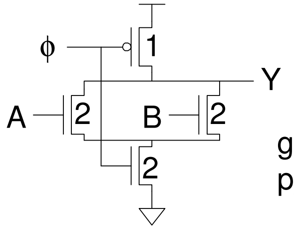


Φp network

2 phase operation:

- Precharge
- Evaluation

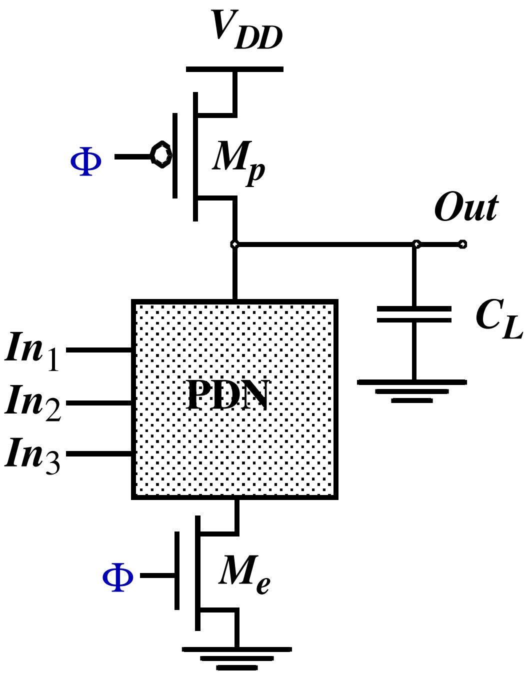
Logical Effort

	Inverter	NAND2	NOR2
unfooted	 g_d = 1/3 p_d = 2/3	 g_d = 2/3 p_d = 3/3	 g_d = 1/3 p_d = 3/3
footed	 g_d = 2/3 p_d = 3/3	 g_d = 3/3 p_d = 4/3	 g_d = 2/3 p_d = 5/3

Dynamic Logic

- N+2 transistors for N-input function
  - Better than 2N transistors for complementary static CMOS
  - Comparable to N+1 for ratio-ed logic
- No static power dissipation
  - Better than ratio-ed logic
- Careful design, clock signal Φ needed

Dynamic Logic: Principles



- **Precharge**

  $\Phi = 0$, *Out* is precharged to V_{DD} by M_p. M_e is turned off, no dc current flows (regardless of input values)

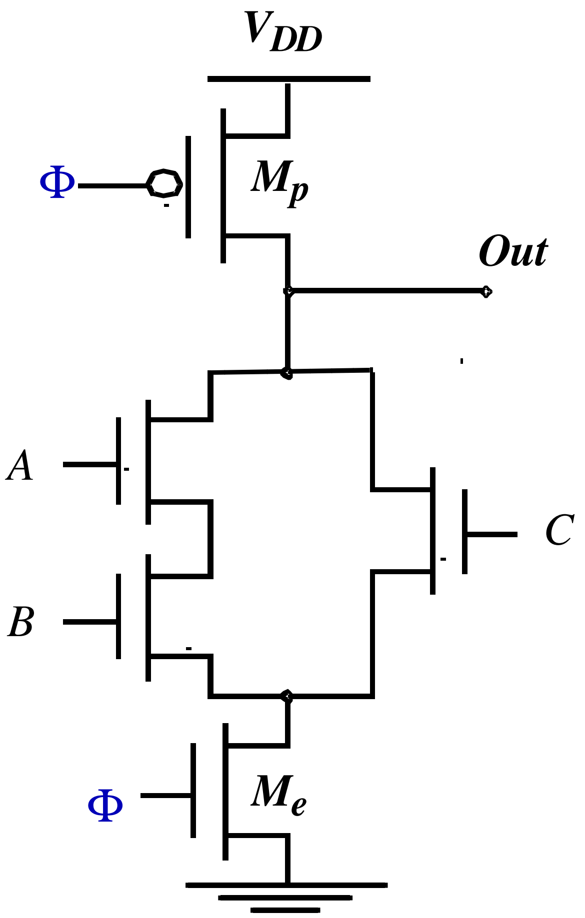
- **Evaluation**

  $\Phi = 1$, M_e is turned on, M_p is turned off. Output is pulled down to zero depending on the values on the inputs. If not, precharged value remains on C_L.

Important: Once *Out* is discharged, it cannot be charged again!
Gate input can make only one transition during evaluation

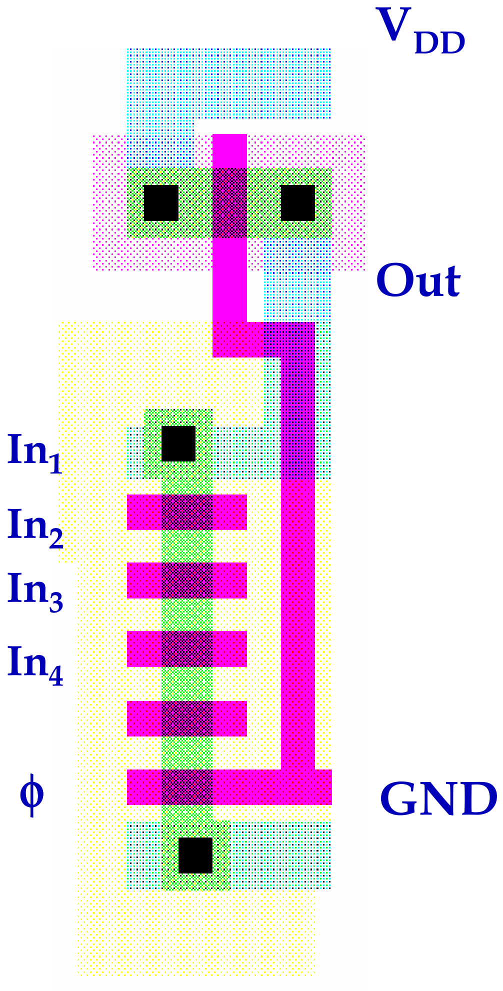
- Minimum clock frequency must be maintained
- Can M_e be eliminated?

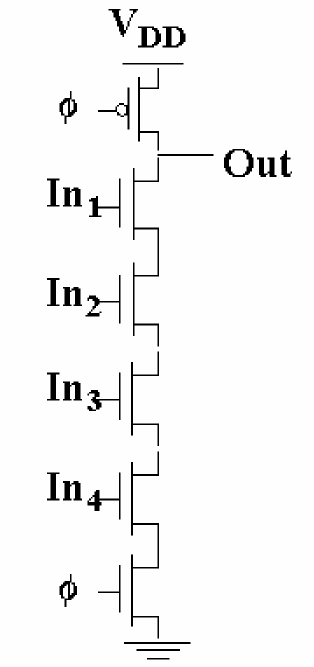
Example



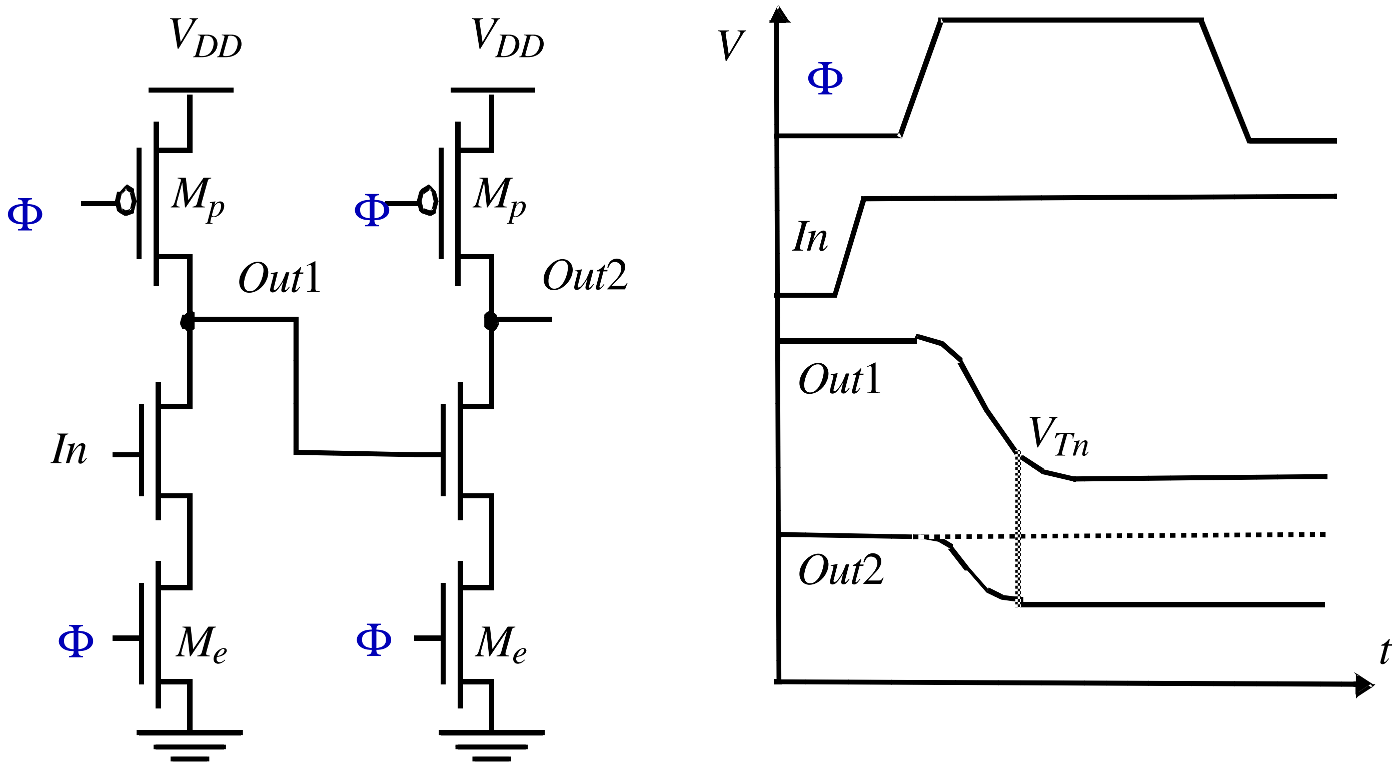
- Ratioless
- No Static Power Consumption
- Noise Margins small (NM_L)
- Requires Clock

Dynamic 4 Input NAND Gate





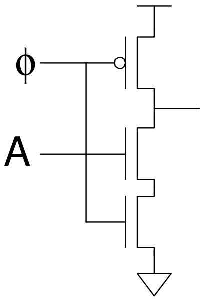
Cascading Dynamic Gates

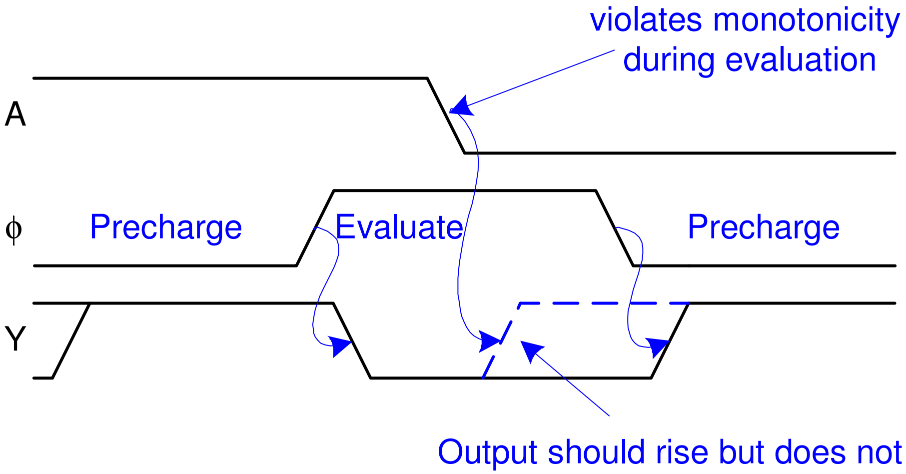


Internal nodes can only make 0-1 transitions during evaluation period

Monotonicity

- Dynamic gates require *monotonically rising* inputs during evaluation
  - – 0 -> 0
  - – 0 -> 1
  - – 1 -> 1
  - – But not 1 -> 0



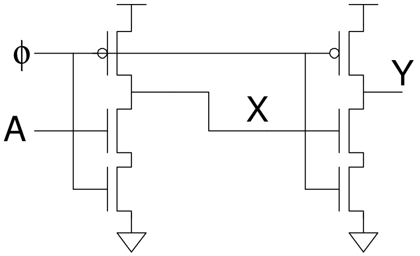


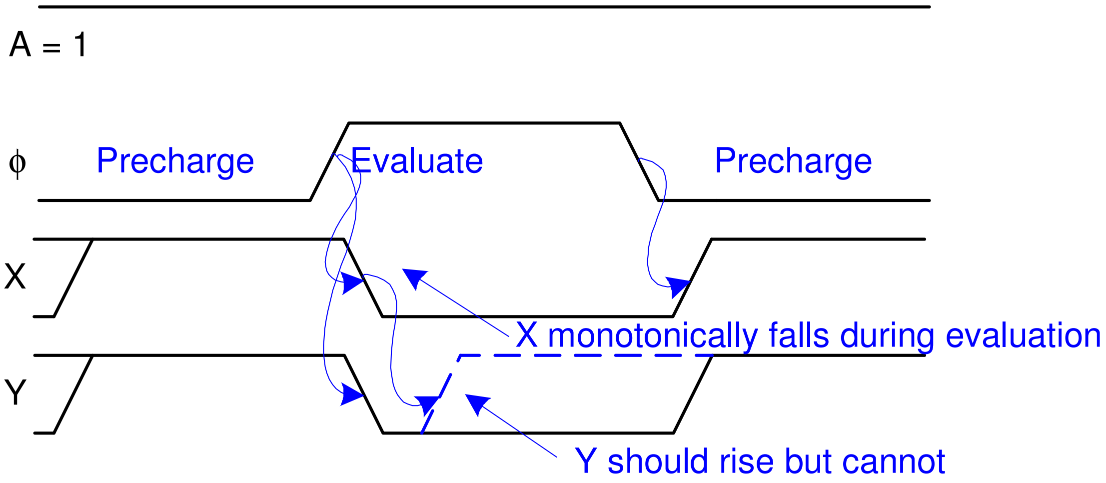
violates monotonicity during evaluation

Output should rise but does not

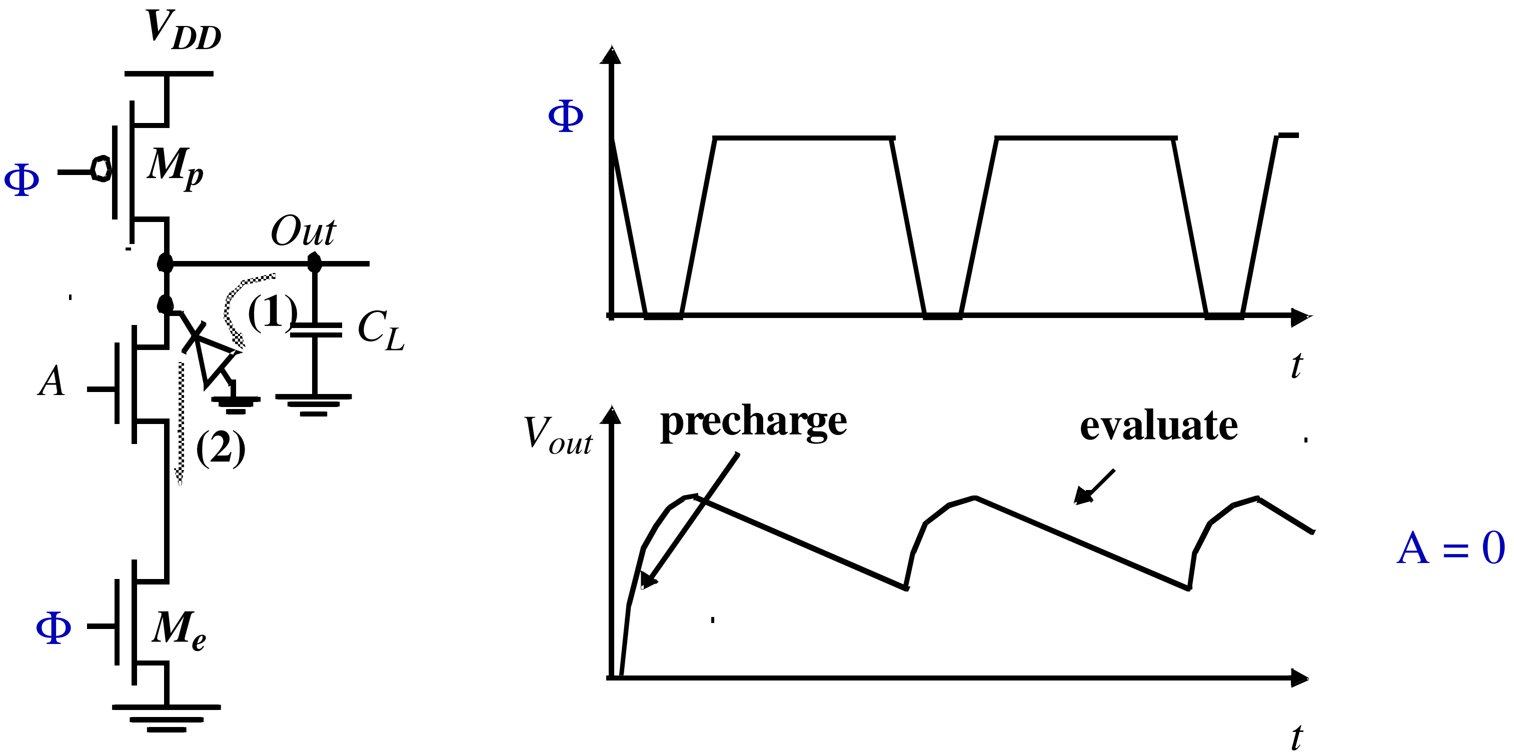
Monotonicity Woes

- But dynamic gates produce monotonically falling outputs during evaluation
- Illegal for one dynamic gate to drive another!





Reliability Problems — Charge Leakage



(a) Leakage sources

(b) Effect on waveforms

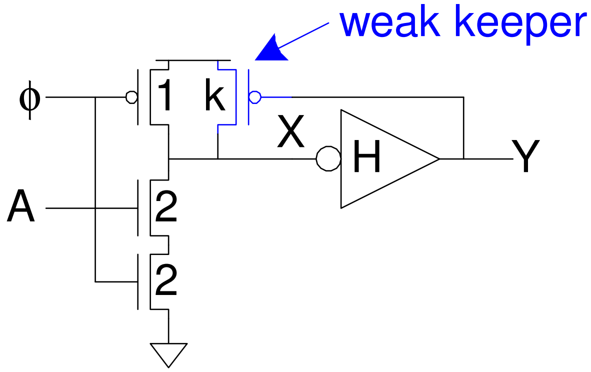
(1) Leakage through reverse-biased diode of the diffusion area

(2) Subthreshold current from drain to source

Minimum Clock Frequency: > 1 MHz

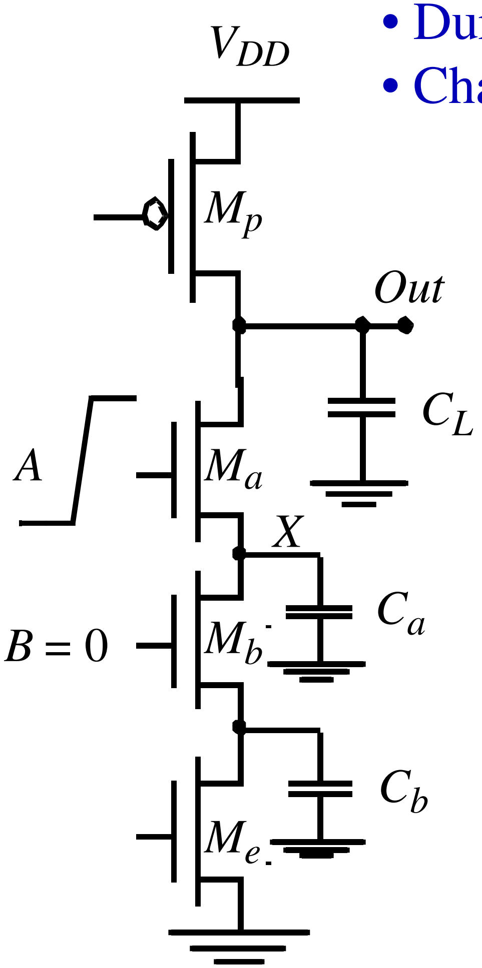
Leakage

- Dynamic node floats high during evaluation
  - Transistors are leaky ($I_{OFF} \neq 0$)
  - Dynamic value will leak away over time
  - Formerly miliseconds, now nanoseconds!
- Use keeper to hold dynamic node
  - Must be weak enough not to fight evaluation



Charge Sharing (redistribution)

- Assume: during precharge, A and B are 0, C_a is discharged
- During evaluation, B remains 0 and A rises to 1
- Charge stored on C_L is now redistributed over C_L and C_a



$$C_L V_{DD} = C_L\, V_{out}(t) + C_a V_X$$

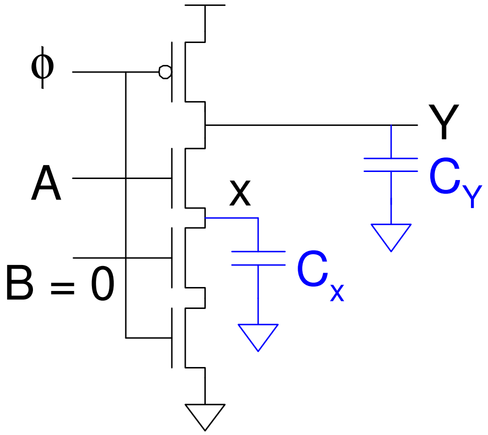
$V_X = V_{DD} - V_t$, therefore

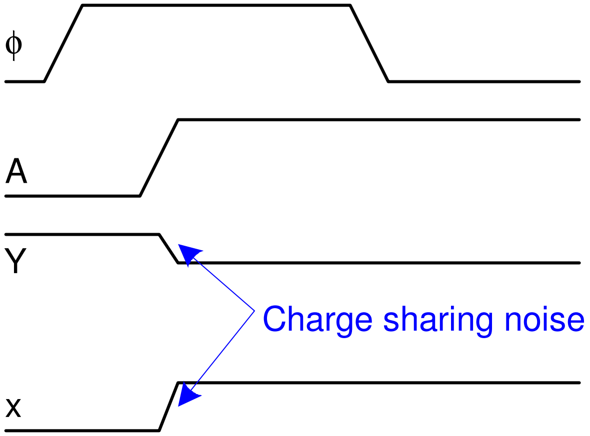
$$\delta V_{out}(t) = V_{out}(t) - V_{DD} = -\frac{C_a}{C_L}(V_{DD}-V_t)$$

Desirable to keep the voltage drop below threshold of pMOS transistor (why?) ⇒ $C_a/C_L < 0.2$

Charge Sharing

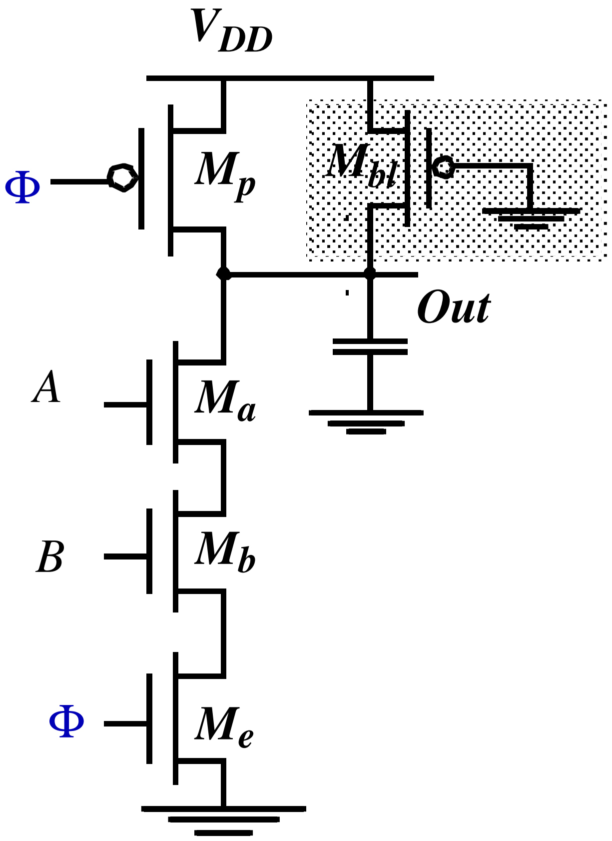
- Dynamic gates suffer from charge sharing



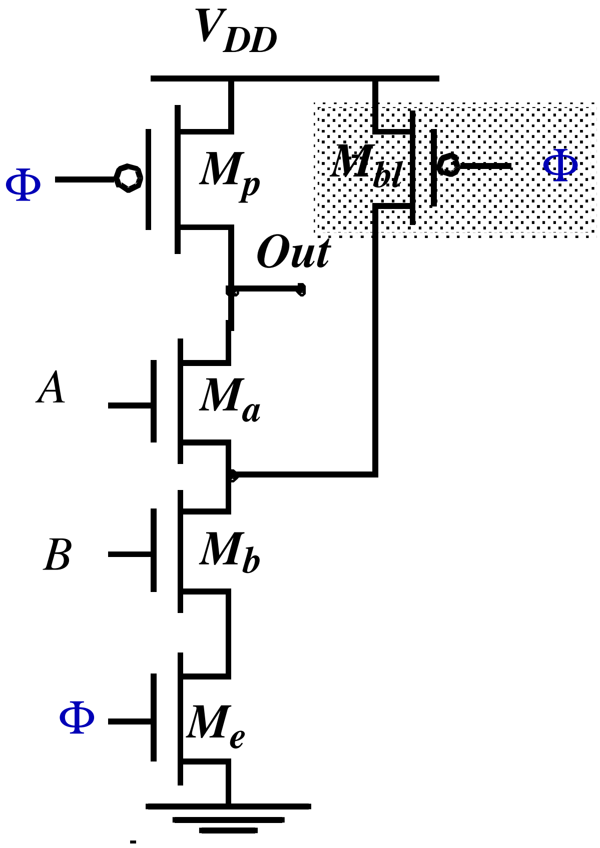


$$V_x = V_Y = \frac{C_Y}{C_x + C_Y} V_{DD}$$

Charge Redistribution - Solutions



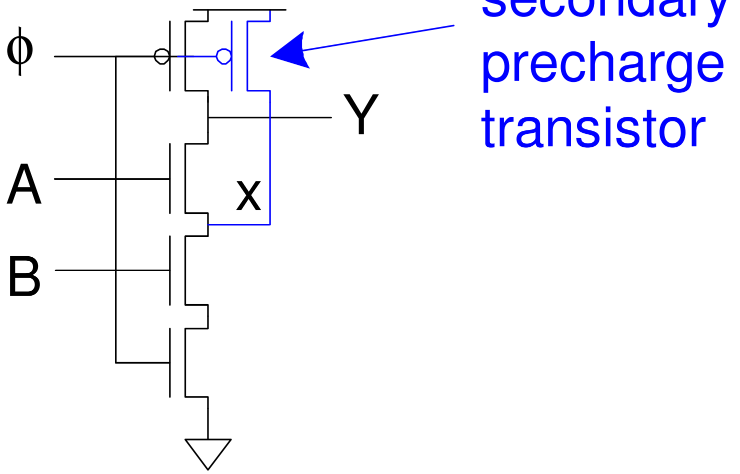
(a) Static bleeder



(b) Precharge of internal nodes

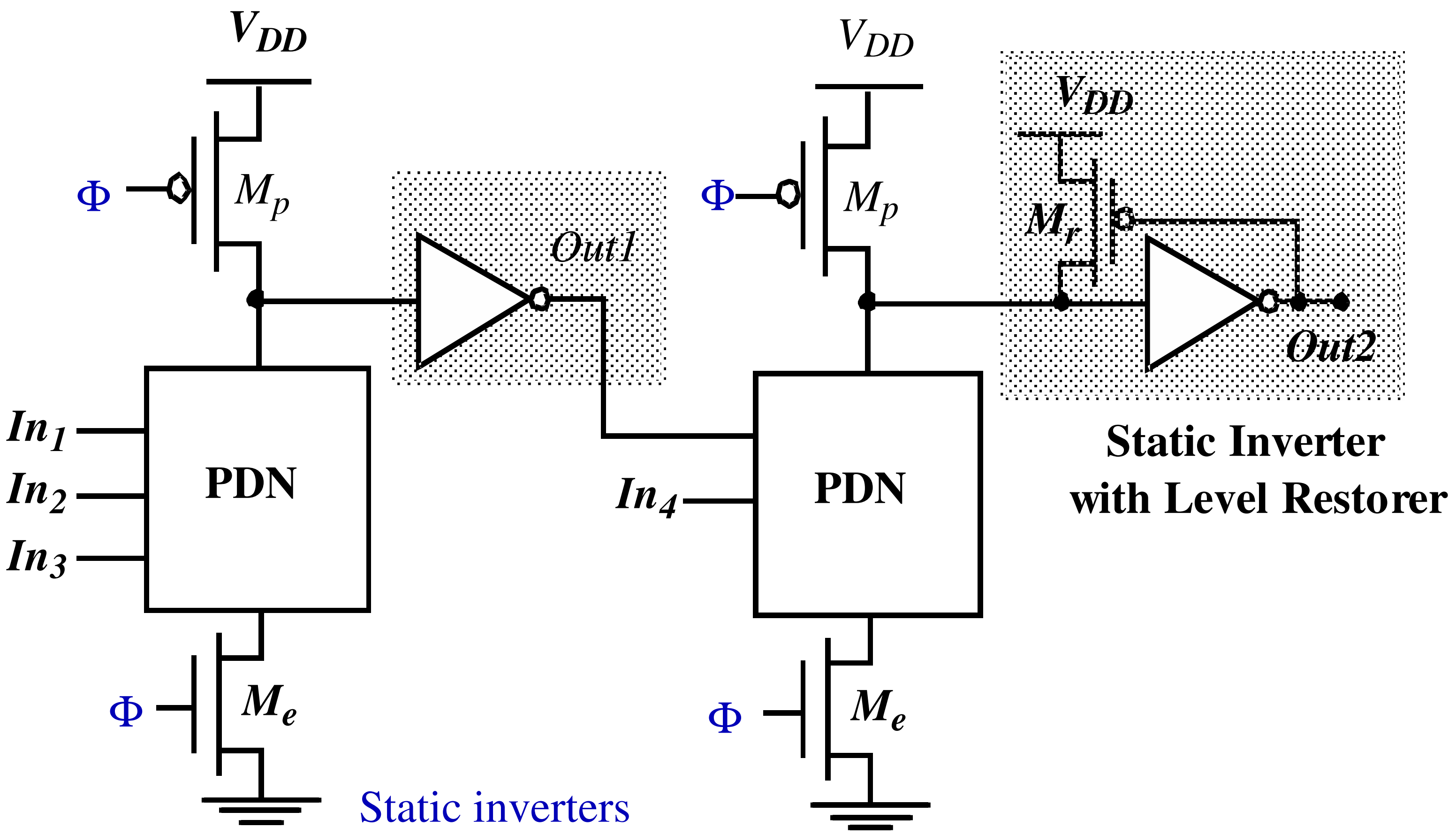
Secondary Precharge

- Solution: add secondary precharge transistors
  - Typically need to precharge every other node
- Big load capacitance C_Y helps as well



secondary
precharge
transistor

Domino Logic

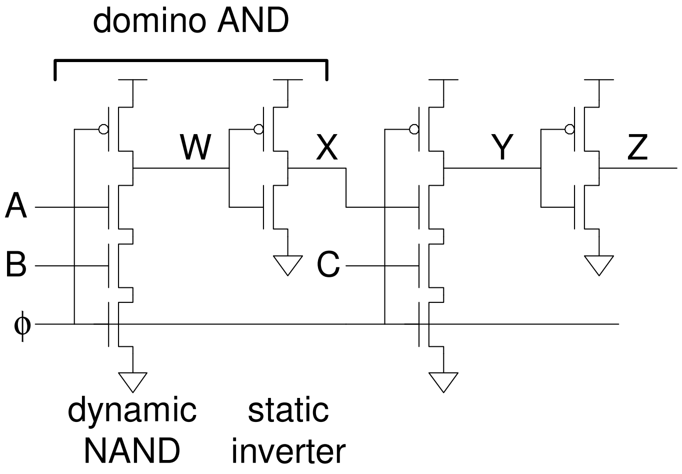


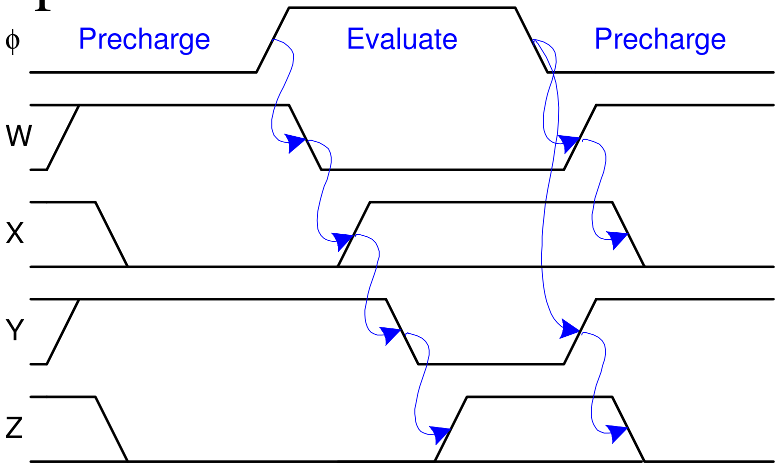
Static Inverter with Level Restorer

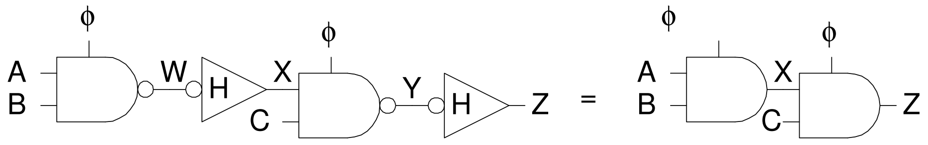
Static inverters between dynamic stages

Domino Gates

- Follow dynamic stage with inverting static gate
  - Dynamic / static pair is called domino gate
  - Produces monotonic outputs





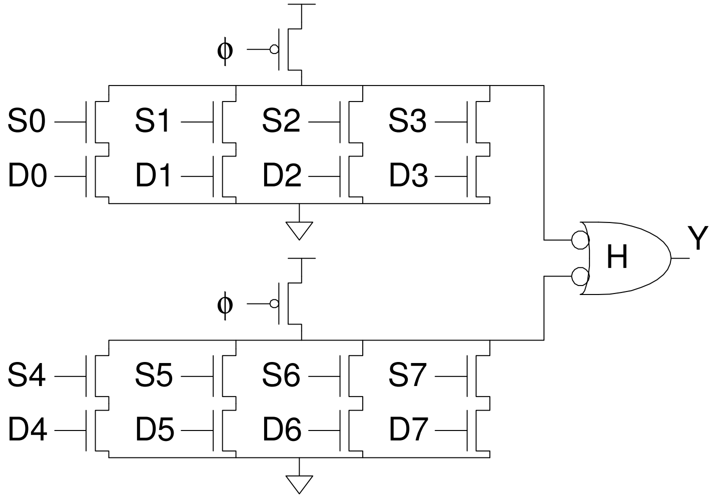


Domino Logic - Characteristics

- Only non-inverting logic
- Very fast - Only 1->0 transitions at input of inverter
- Precharging makes pull-up very fast
- Adding level restorer reduces leakage and charge redistribution problems
- Optimize inverter for fan-out

Domino Optimizations

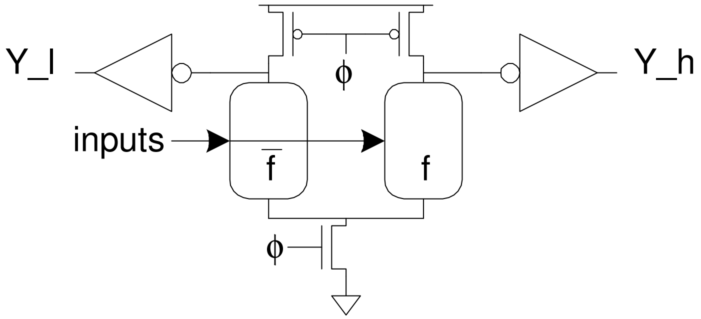
- Each domino gate triggers next one, like a string of dominos toppling over
- Gates evaluate sequentially but precharge in parallel
- Thus evaluation is more critical than precharge
- HI-skewed static stages can perform logic



Dual-Rail Domino

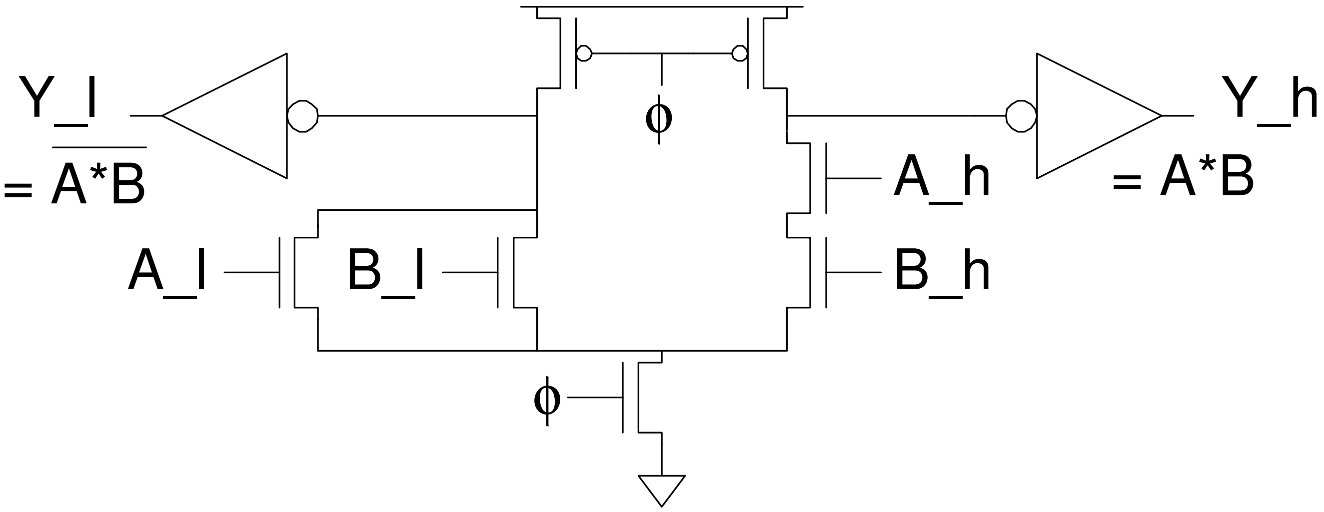
- Domino only performs noninverting functions:
  - AND, OR but not NAND, NOR, or XOR
- Dual-rail domino solves this problem
  - Takes true and complementary inputs
  - Produces true and complementary outputs

sig_h	sig_l	Meaning
0	0	Precharged
0	1	‘0’
1	0	‘1’
1	1	invalid



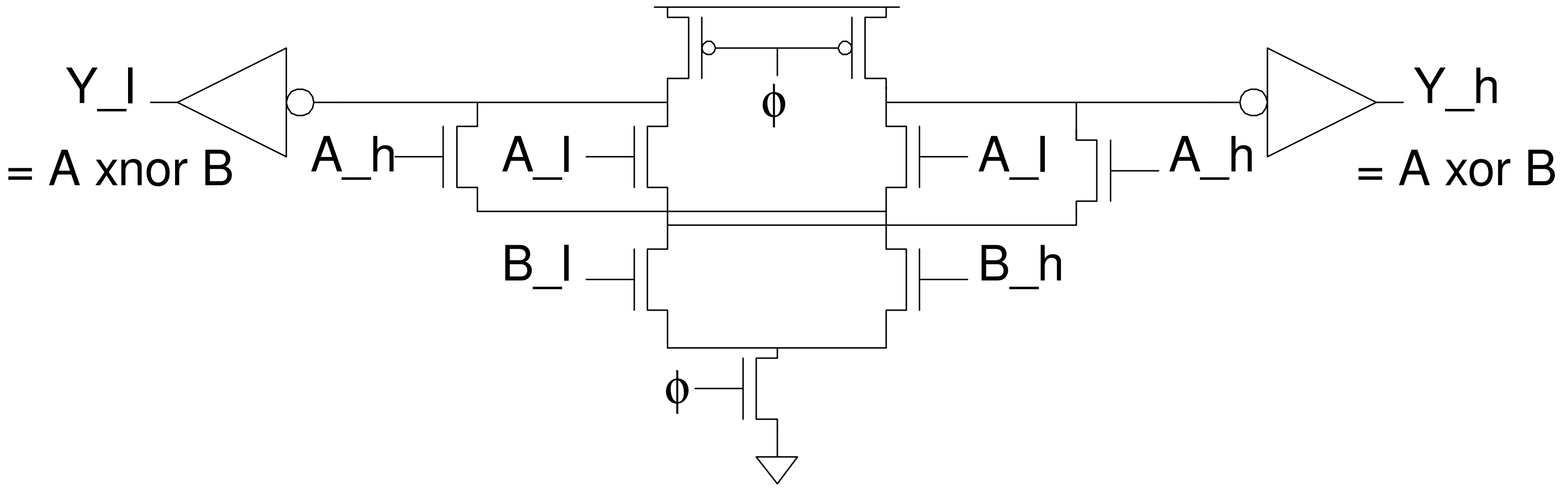
Example: AND/NAND

- Given A_h, A_l, B_h, B_l
- Compute Y_h = A * B, Y_l = ~(A * B)
- Pulldown networks are conduction complements



Example: XOR/XNOR

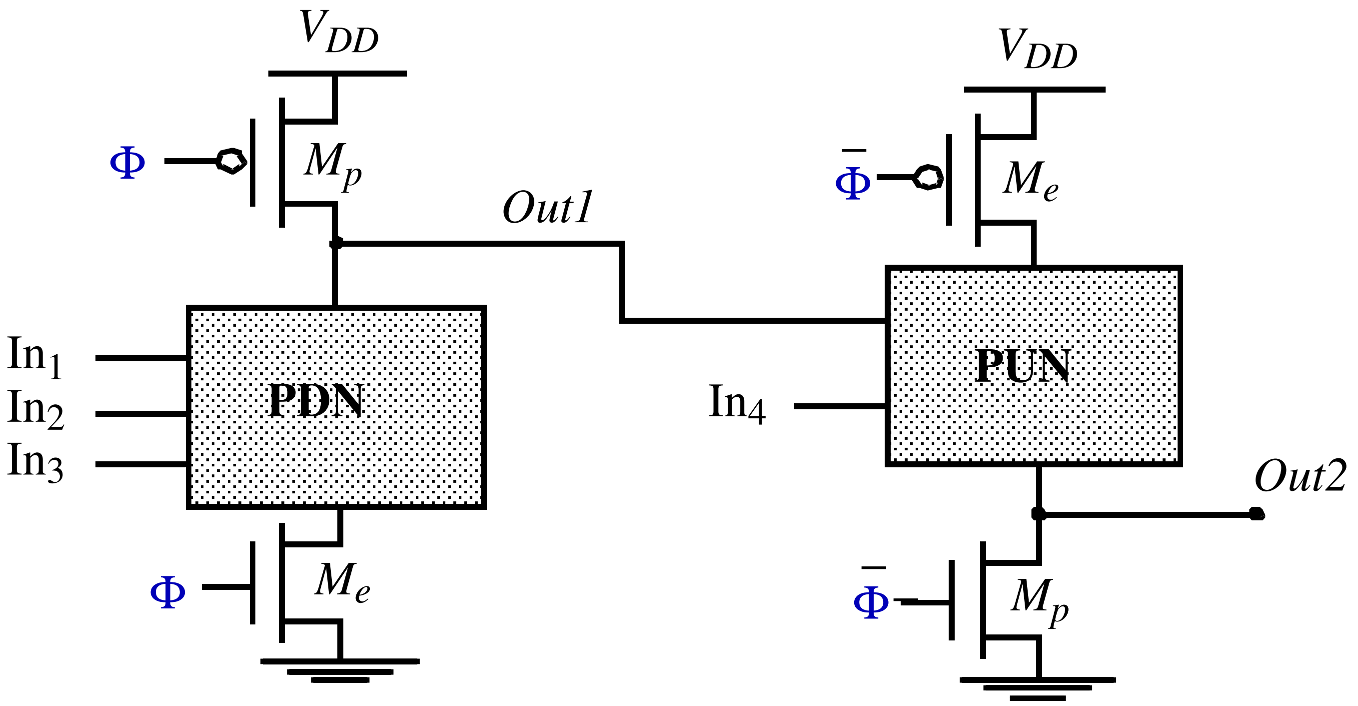
- Sometimes possible to share transistors



Domino Summary

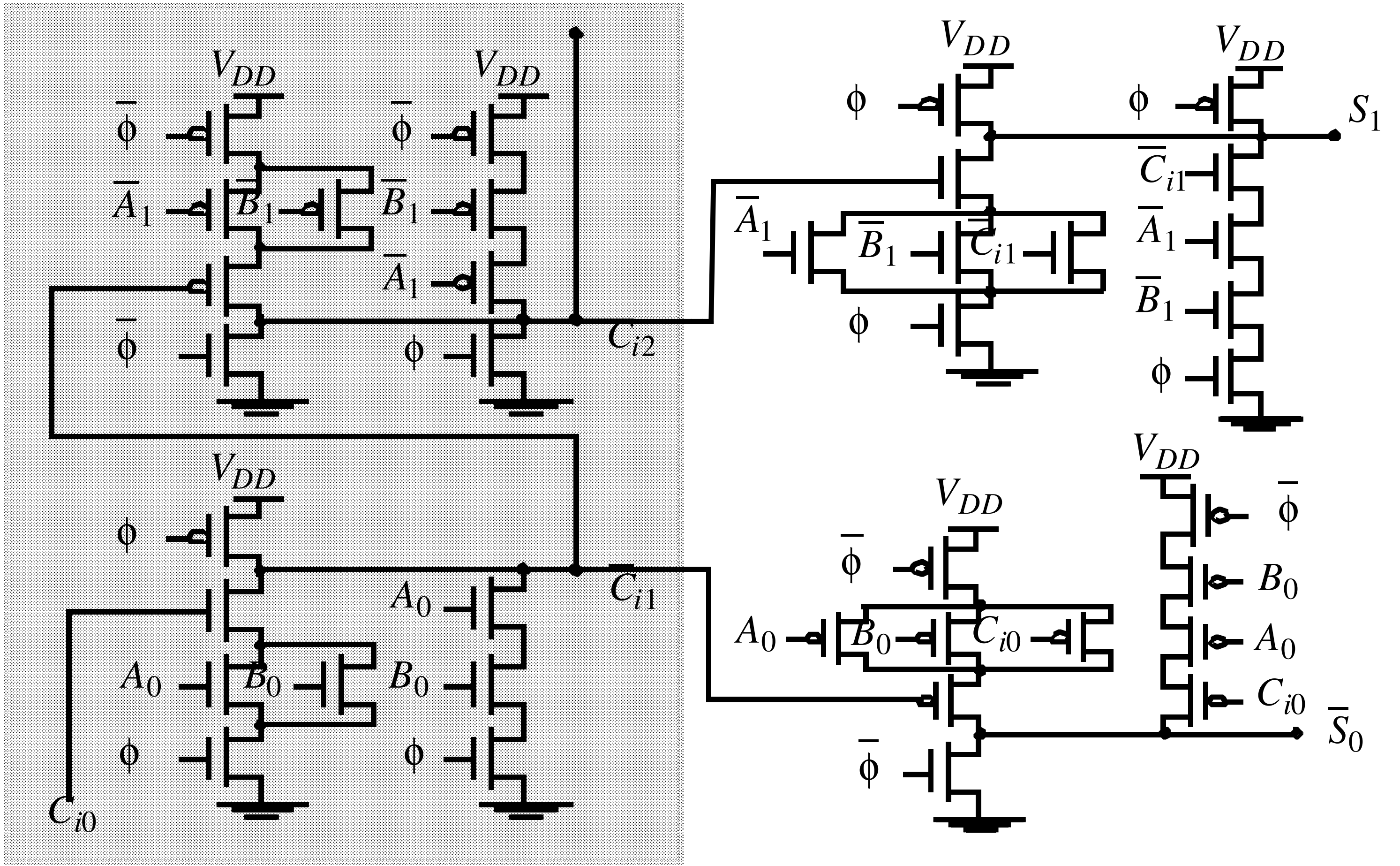
- Domino logic is attractive for high-speed circuits
  - 1.5 – 2x faster than static CMOS
  - But many challenges:
    - Monotonicity
    - Leakage
    - Charge sharing
    - Noise
- Widely used in high-performance microprocessors

np-CMOS (Zipper CMOS)



- Only 1-0 transitions allowed at inputs of PUN
- Used a lot in the Alpha design

np CMOS Adder



CMOS Circuit Styles - Summary

Style	Ratioed	Static Power	# transistors	Area (μm^2)	Propagation Delay (nsec)
Complementary	No	No	8	533	0.61
Pseudo-NMOS	Yes	Yes	5	288	1.49
CPL	No	No	14	800	0.75
Dynamic (NP)	No	No	6	212	0.37

4-input NAND Gate