

Full-Custom CMOS 3-Bit Synchronous Counter

Transistor-Level Design and Post-Layout Characterization

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Abstract— This work presents a full-custom 3-bit synchronous CMOS counter implemented at transistor level and operating at $V_{DD} = 0.65$ V. The design was fully laid out and validated post-layout, with measured delays ranging from 90 ps to 172 ps and stable operation under high-frequency excitation. *Intrinsic gate delay does not define system f_{\max} ; sequential timing constraints and clock integrity ultimately bound performance.*

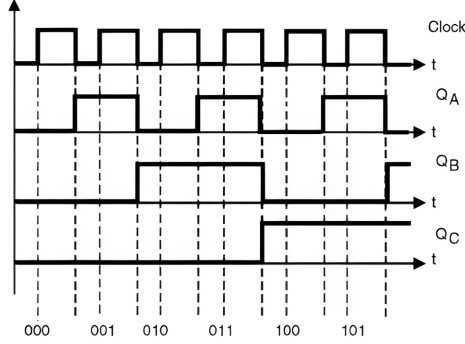


Figure 1: Expected synchronous counting sequence (conceptual timing diagram).

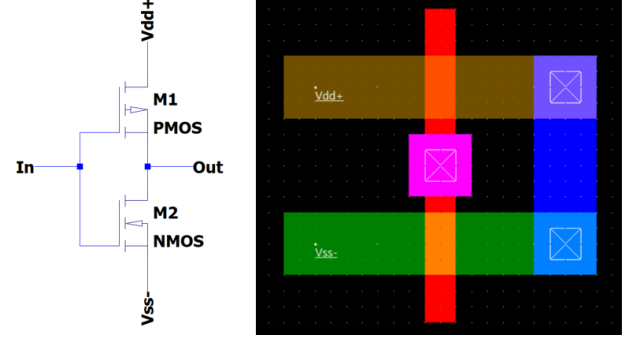


Figure 2: CMOS inverter layout used as sizing and parasitic reference.

1 Design Goals and Context

Objective: implement and validate a **fully synchronous 3-bit binary up-counter** at **transistor level**, including layout and post-layout verification.

Target specifications

- 3-bit synchronous up-counter outputs (Q_2, Q_1, Q_0)
- Edge-triggered clocking (master-slave storage)
- Supply voltage: $V_{DD} = 0.65$ V (low-voltage regime)
- Post-layout transient validation and corner awareness (min/typ/max)

Engineering intent

- Apply full-custom CMOS design principles
- Link parasitics to waveform behavior
- Distinguish gate delay from sequential timing limits

2 Logic Architecture

The synchronous next-state equations are:

$$\begin{aligned} Q_0^+ &= \overline{Q_0} \\ Q_1^+ &= Q_1 \oplus Q_0 \\ Q_2^+ &= Q_2 \oplus (Q_1 Q_0) \end{aligned}$$

Each Q_i^+ drives the D input of an edge-triggered master-slave D flip-flop. This guarantees that state updates occur only around the clock edge, preventing level-sensitive transparency.

The expected binary evolution is illustrated in Figure 1.

3 Transistor-Level Building Blocks

3.1 CMOS Inverter (Reference Cell)

The inverter is the *electrical reference* used to reason about sizing, noise margins, and rise/fall symmetry.

The implemented layout is shown in Figure 2.

What “good” sizing tries to achieve

- PMOS width $>$ NMOS width to compensate mobility ($\mu_p < \mu_n$)
- Comparable pull-up/pull-down strength for symmetric t_{pLH} and t_{pHL}
- Low output resistance while keeping input capacitance under control

Why small deviations matter at 0.65 V At low V_{DD} , overdrive ($V_{GS} - V_T$) is reduced, so current drops sharply and timing becomes more sensitive to: (1) width ratio errors, (2) stacked devices (effective resistance), (3) parasitic capacitances (especially C_{gd}), and (4) interconnect RC.

3.2 NAND Gate (Static CMOS)

NAND gates implement the combinational portions required by XOR/AND decompositions.

The full-custom layout of this gate is shown in Figure 3.

Stack effect and sizing

- Two series NMOS devices increase effective R_{on} and degrade t_{pHL}
- Common mitigation: up-size stacked NMOS or limit stack depth

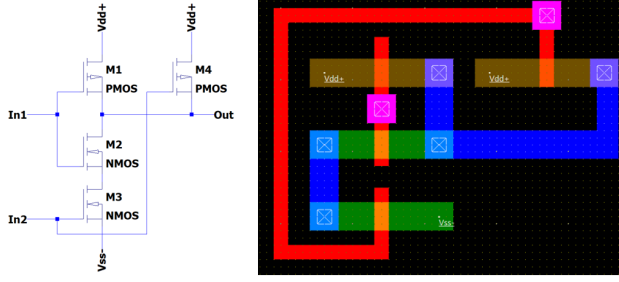


Figure 3: CMOS NAND layout (routing and diffusion sharing visible).

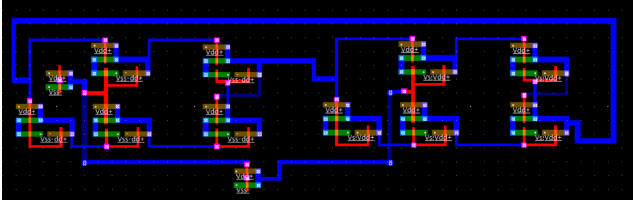


Figure 4: Transistor-level master-slave D flip-flop layout.

- PMOS network is in parallel for NAND, typically less critical for pull-up

This gate is a primary source of *charge sharing* and *dynamic internal node behavior* when multiple transistors switch near-simultaneously, especially under fast clocks.

3.3 Master-Slave D Flip-Flop (Edge-Triggered Storage)

A master-slave topology was selected to enforce edge-triggered behavior and isolate combinational logic from the stored state during most of the clock cycle.

The implemented flip-flop layout is shown in Figure 4.

Why this matters physically

- Avoids level-sensitive transparency that can amplify hazards in the logic cone
- Provides a well-defined timing interface: t_{CQ} , t_{setup} , t_{hold}
- However, introduces internal dynamic nodes whose parasitics impact timing and waveform integrity

4 Full Counter Layout Integration

The full-custom integration (logic + 3 DFFs + clock distribution) is shown in Figure 5.

Layout-level priorities

- Clock routing as a first-class signal (skew and edge quality matter)
- Interconnect length minimization on critical nodes (D inputs, internal FF nodes)
- Diffusion sharing where safe to reduce area/capacitance, but avoiding unintended coupling
- Local symmetry where feasible to reduce systematic mismatch

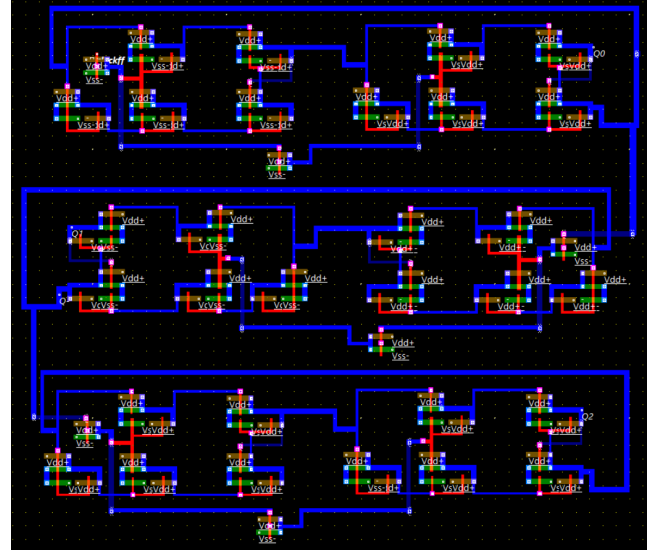


Figure 5: Complete 3-bit synchronous counter full-custom layout.

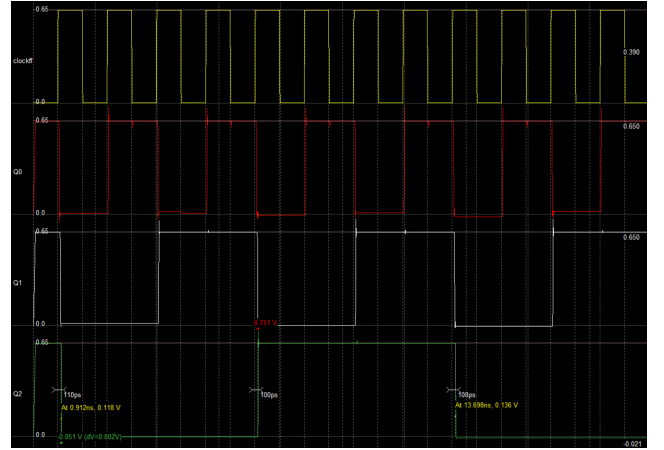


Figure 6: Post-layout transient waveforms showing correct synchronous counting behavior.

5 Post-Layout Validation (Transient)

Simulation conditions

- Tool: Microwind (post-layout extracted behavior)
- $V_{DD} = 0.65 \text{ V}$, $T = 25^\circ\text{C}$
- High-frequency excitation used for stress validation

Representative post-layout waveforms are shown in Figure 6.

Functional outcome The counter follows the expected binary sequence:

$$000 \rightarrow 001 \rightarrow 010 \rightarrow \dots \rightarrow 111$$

No sustained oscillation or metastable lock was observed in the captured window.

6 Signal Integrity: Why Overshoot/Undershoot Appears

Measured waveforms exhibit:

Table 1: Post-layout propagation delays across process corners.

Metric	Min	Typ	Max
t_{pLH} (ps)	154	100	90
t_{pHL} (ps)	172	110	98

- Residual voltages around 100 mV to 140 mV on some nodes
- Minor undershoot and small spikes around transitions

Physical causes (post-layout reality)

- **Miller coupling (C_{gd}):** fast input transitions inject charge into the output
- **Interconnect capacitance and coupling:** neighboring wires and diffusion add dynamic crosstalk
- **Charge sharing in stacked networks:** internal nodes exchange charge during switching
- **Finite clock slope and clock feedthrough:** FF internal nodes are sensitive to clock edge quality
- **Low V_{DD} noise margins:** the same absolute disturbance represents a larger fraction of logic swing

Engineering interpretation These artifacts do *not* imply logic failure; correct operation requires valid noise margins and node settling before the clock edge.

7 Timing: Consistent Interpretation

7.1 Propagation Delay Measurements (Gate-Level)

Propagation delays were measured from input 50% crossing to output 50% crossing under post-layout conditions. The measured propagation delays are summarized in Table 1.

What these numbers actually mean Delays in the 90 ps to 172 ps range indicate *very fast intrinsic switching* of individual stages under the measured loading conditions.

7.2 Why Gate Delay \neq System f_{\max}

A synchronous system must satisfy, for every reg-to-reg path:

$$T_{clk} \geq t_{CQ} + t_{logic} + t_{setup} + t_{skew} + t_{margin}$$

Therefore, even if individual gates are sub-ns, practical frequency can be limited by:

- **t_{CQ} of master-slave FF:** internal dynamic nodes and clock feedthrough add delay
- **Setup/hold:** low- V_{DD} reduces speed and margins
- **Clock distribution:** skew and edge degradation affect sampling instant
- **Worst-case internal switching:** simultaneous switching noise, charge sharing, and coupling

Table 2: Total power consumption across process corners.

Condition	Min	Typ	Max
P_{tot} (μ W)	3.66	27.62	381.4

Sanity check (unit consistency) If a design’s key delays are on the order of 100 ps, the corresponding time scale is 0.1 ns, i.e., *multi-GHz intrinsic potential*. Any reported f_{\max} in the tens of MHz range must be justified by full sequential timing measurements (including t_{CQ} , t_{setup} , and clock integrity), not by gate t_p alone.

8 Power Characterization

Dynamic power follows the CMOS relationship:

$$P_{dyn} \approx \alpha C V_{DD}^2 f$$

Measured total power across corners is summarized in Table 2.

Interpretation

- Large corner spread is expected: mobility, V_T , and effective drive strengths shift both delay and short-circuit components
- At low V_{DD} , leakage and short-circuit contributions can become more sensitive to process
- The measured trend remains consistent with the quadratic V_{DD}^2 dependence of dynamic power

9 Engineering Takeaways (Analog Devices-Oriented)

This project demonstrates full-custom CMOS competence:

- **Transistor-level design** with static logic and edge-triggered storage
- **Layout-aware analysis** of parasitics and routing impact
- **Signal integrity insight** (coupling, Miller effect, charge sharing)
- **Sequential timing discipline** beyond isolated gate delay
- **Power-performance awareness** across process corners

A 3-bit synchronous counter was implemented in full-custom CMOS at $V_{DD} = 0.65$ V and validated post-layout. Propagation delays range from 90 ps to 172 ps, with parasitic-driven waveform artifacts remaining compatible with correct operation. *System performance is ultimately bounded by sequential timing closure and clock integrity, not by an isolated gate delay.*