Nyquist-Rate D/A Converters
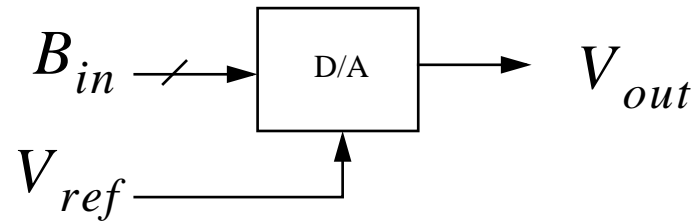
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D/A Converter Basics.

- B_{in} is a digital signal (or word),

$$B_{in} = b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N} \tag{1}$$

- b_i equals a "1" or a "0" (i.e. a binary digit).
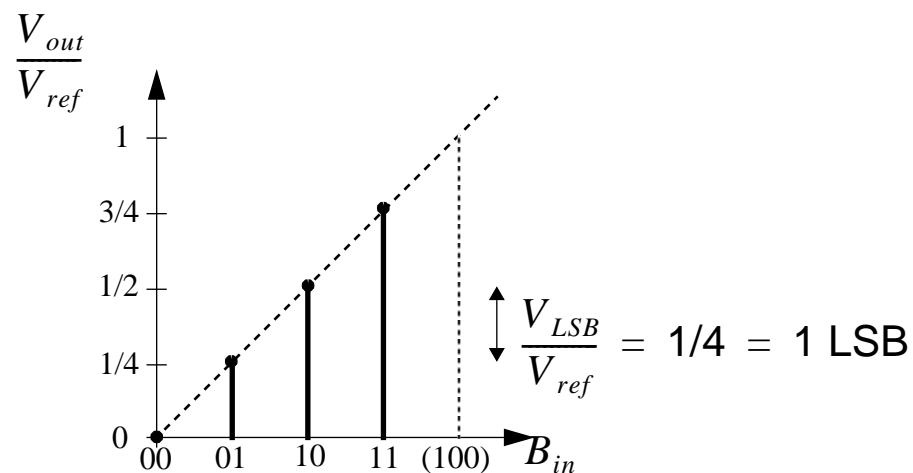
- V_{ref} — an analog reference; V_{out} — output .

$$V_{out} = V_{ref}(b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N}) \tag{2}$$

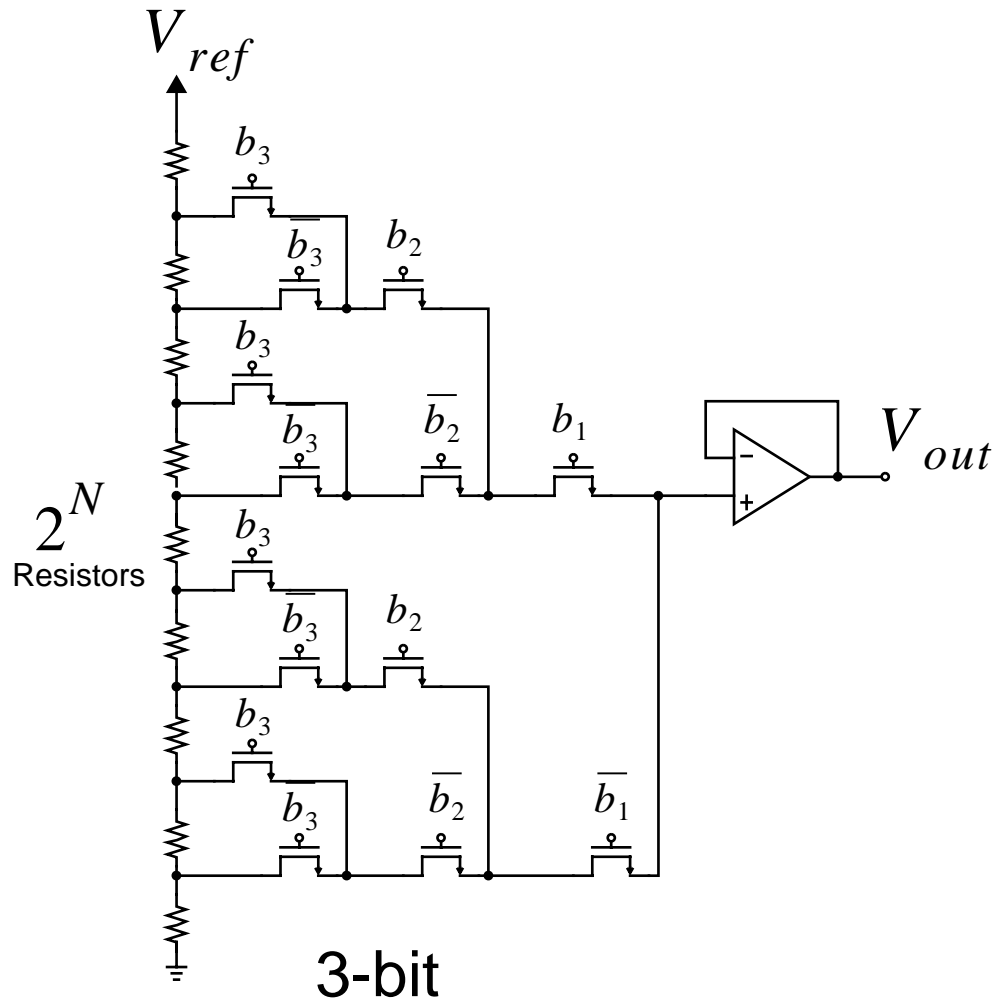- **Define** V_{LSB} to be LSB signal change, $V_{LSB} \equiv V_{ref}/2^N$

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D/A Converter Basics

- For errors, define "units" of LSB 1 LSB $= 1/2^N$
- A ***multiplying*** D/A allows V_{ref} to be a ***varying input***
  — V_{out} proportional to multiplication of V_{ref} and B_{in}.
- For ***ideal*** D/A , output signal is a ***well defined value***
 — no quantization error!

$$\frac{V_{LSB}}{V_{ref}} = 1/4 = 1\text{ LSB}$$

D/A Resistor-String (Hamadé, JSSC, Dec. 1978)

V_{ref}

b_3
$\overline{b_3}$
b_2
b_3
$\overline{b_3}$
$\overline{b_2}$
b_1

V_{out}

2^N Resistors

b_3
$\overline{b_3}$
b_2
b_3
$\overline{b_3}$
$\overline{b_2}$
$\overline{b_1}$

3-bit

- Guaranteed monotonic

- Integrated with better than 10-bits absolute accuracy.

- Delay through the switch network major speed limitation

- Resistors might be realized using polysilicon

- If n-channel only used, can be laid out small

- Requires 2^N resistors

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D/A Resistor-String — Digital Decoding

V_{ref}

2^N Resistors

3 to 1 of 8 decoder

b_1

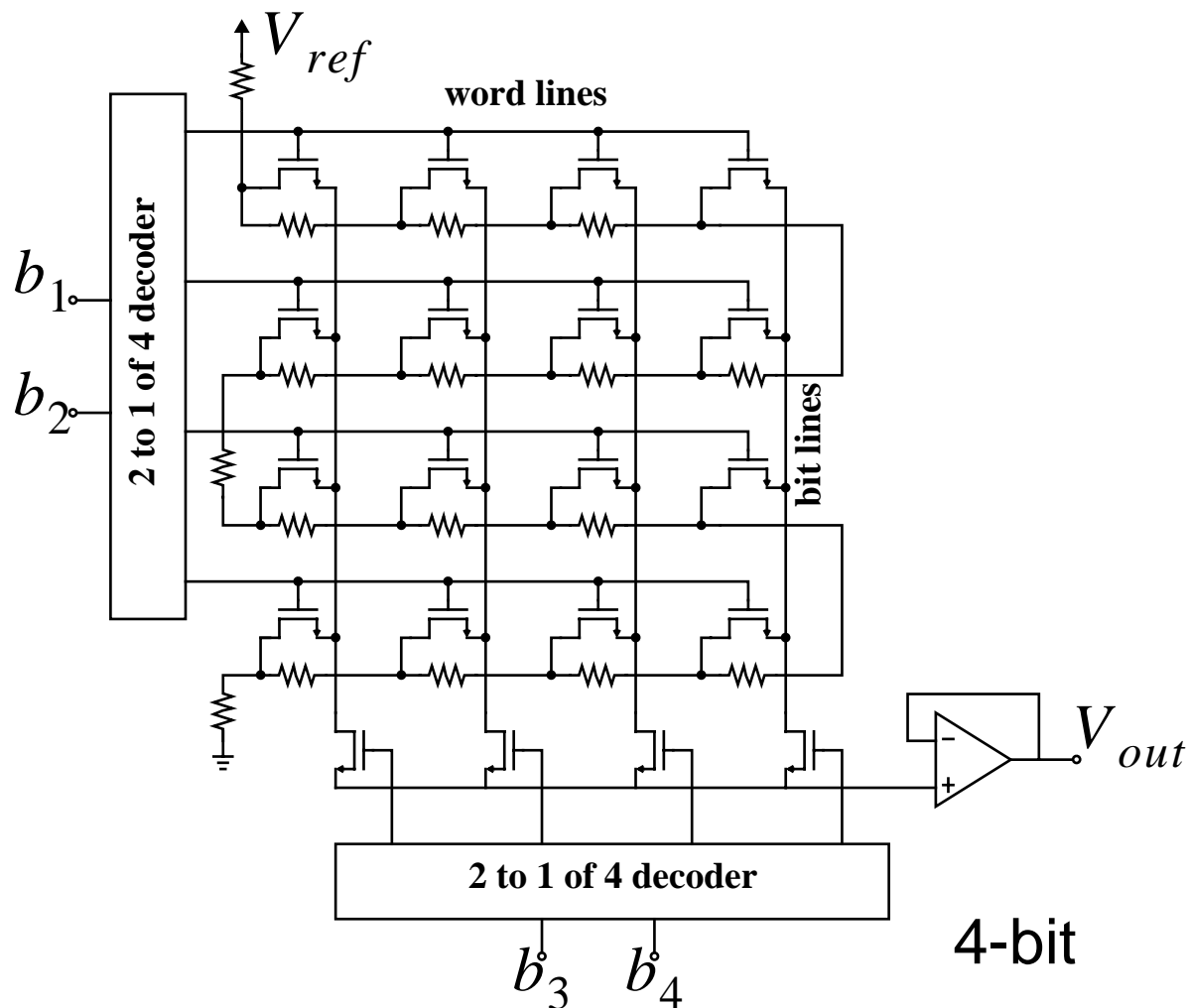b_2

b_3

V_{out}

3-bit
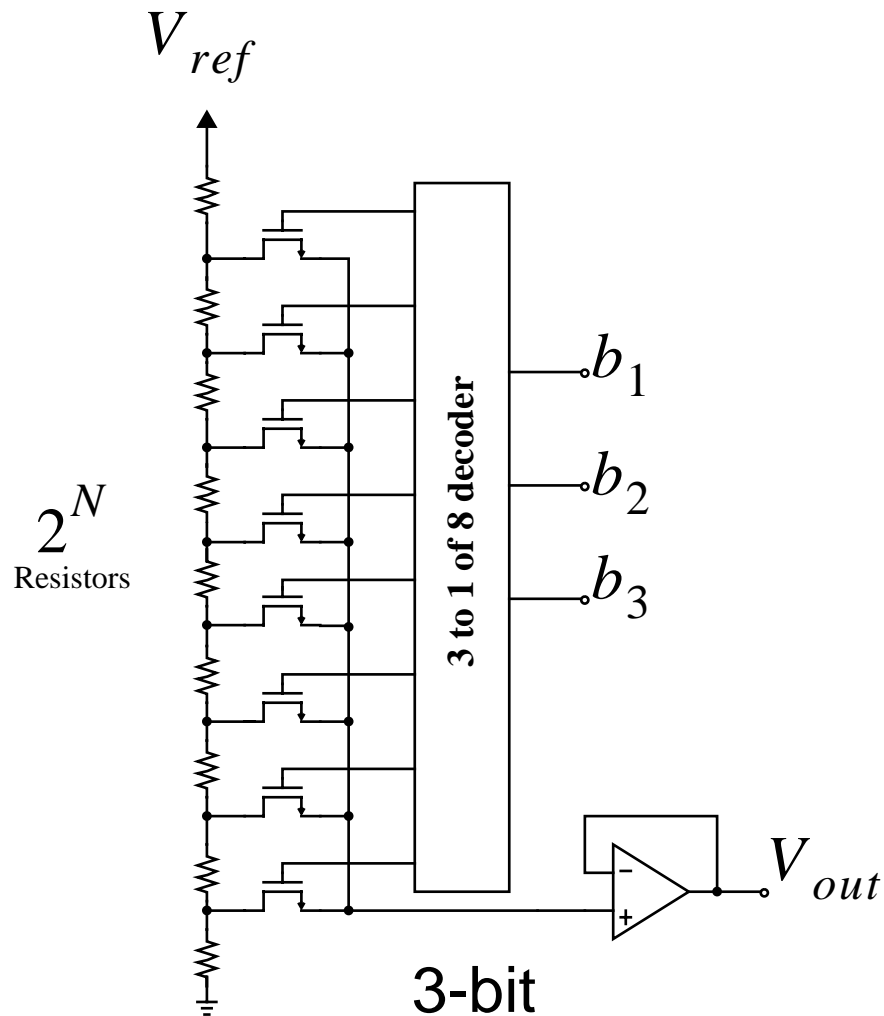
- Higher speed implementation (less resistance thru transistors)

- Large cap load on buffer input

- Can pipeline digital decoding for faster speed

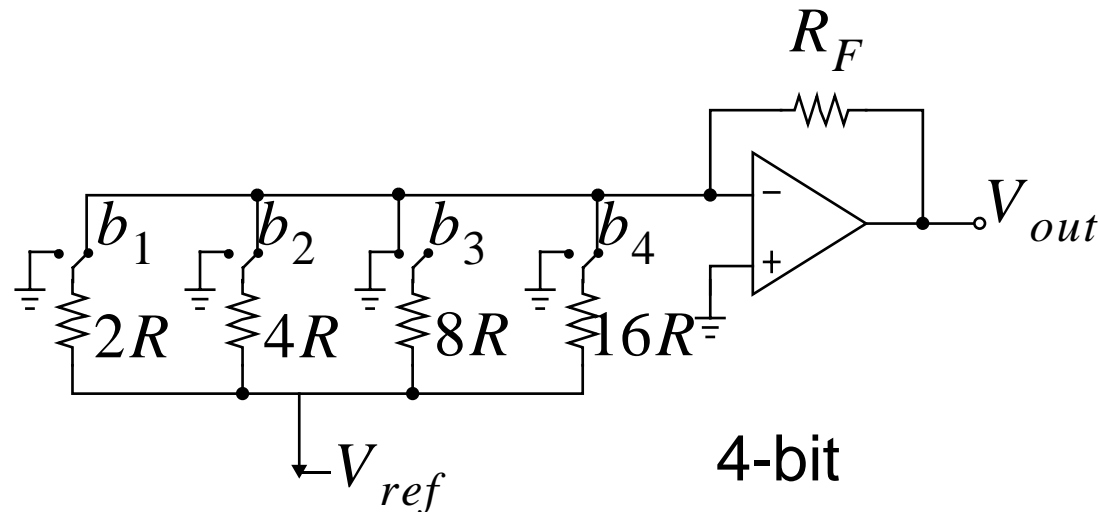- Requires 2^N resistors

Folded-resistor-string D/A

- (Abrial, JSSC, Dec. 1988)

- Less capacitance load over the single bus approach

- Requires 2^N resistors
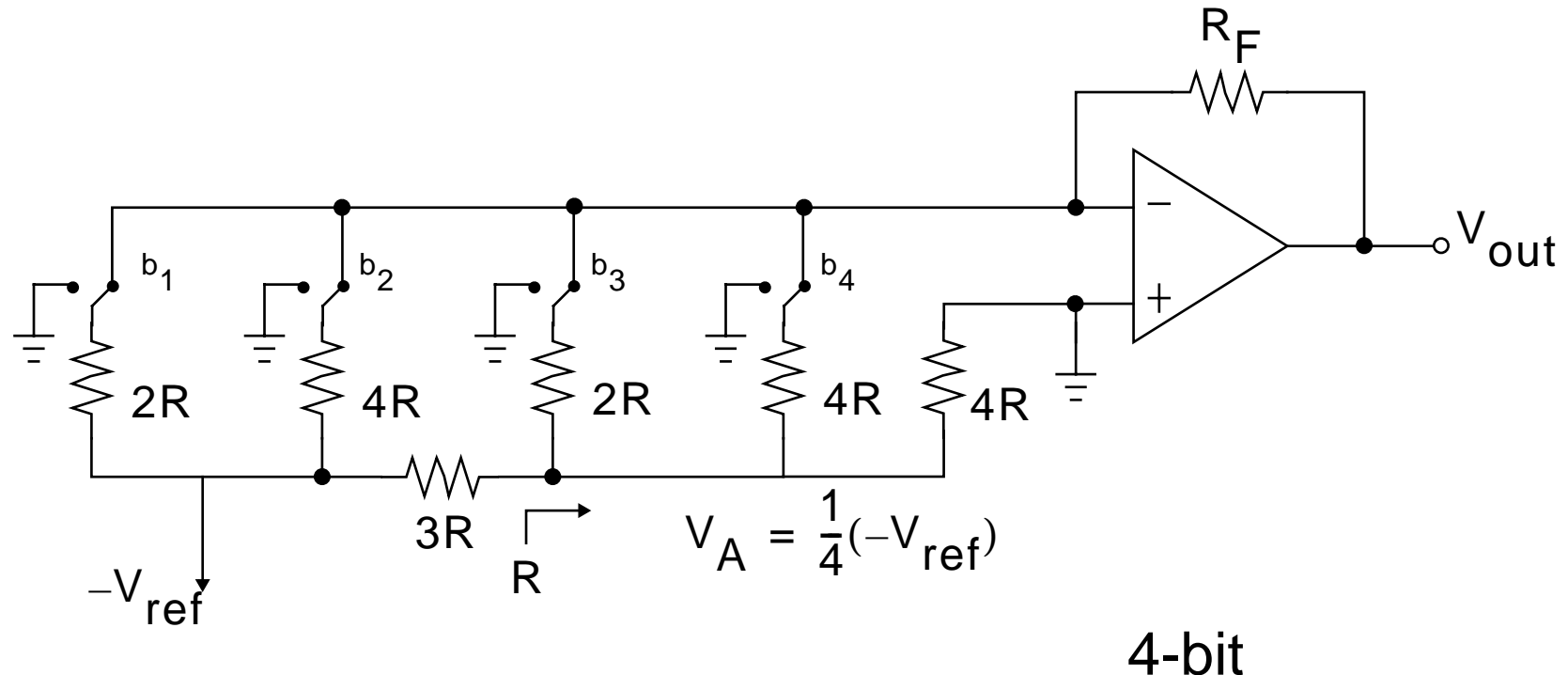
4-bit

Binary-Weighted Resistor D/A's.

4-bit

$$V_{\text{out}} = -R_F V_{ref}\left(-\frac{b_1}{2R} - \frac{b_2}{4R} - \frac{b_3}{8R} - \ldots\right)$$

(3)

- Only N resistors

- Resistor and current ratios are on the order of 2^N

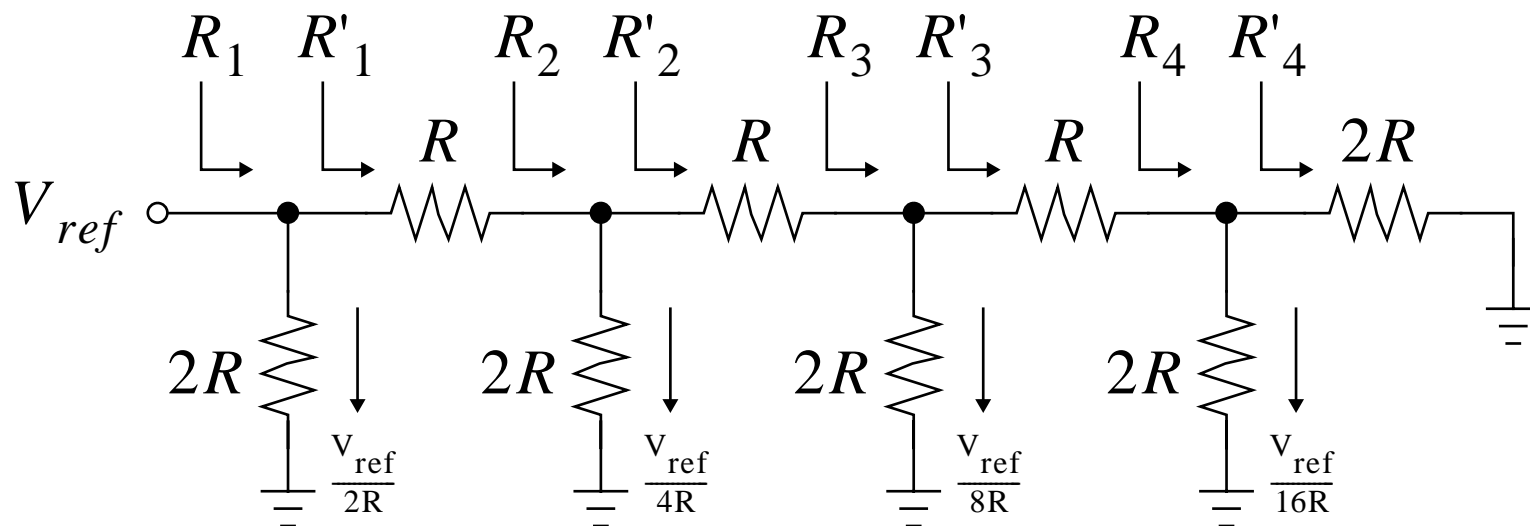- No guarantee of monotonicity.

- Prone to glitches (more later).

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Reduced Spread Binary Resistor D/A

$$V_A = \frac{1}{4}(-V_{ref})$$

4-bit

- Reduced resistor spread
- Keep repeating this procedure —> R-2R ladder

R-2R Based D/A Converters

$$R'_4 = 2R$$
$$R_4 = 2R \parallel 2R = R$$
$$R'_3 = R + R_4 = 2R$$
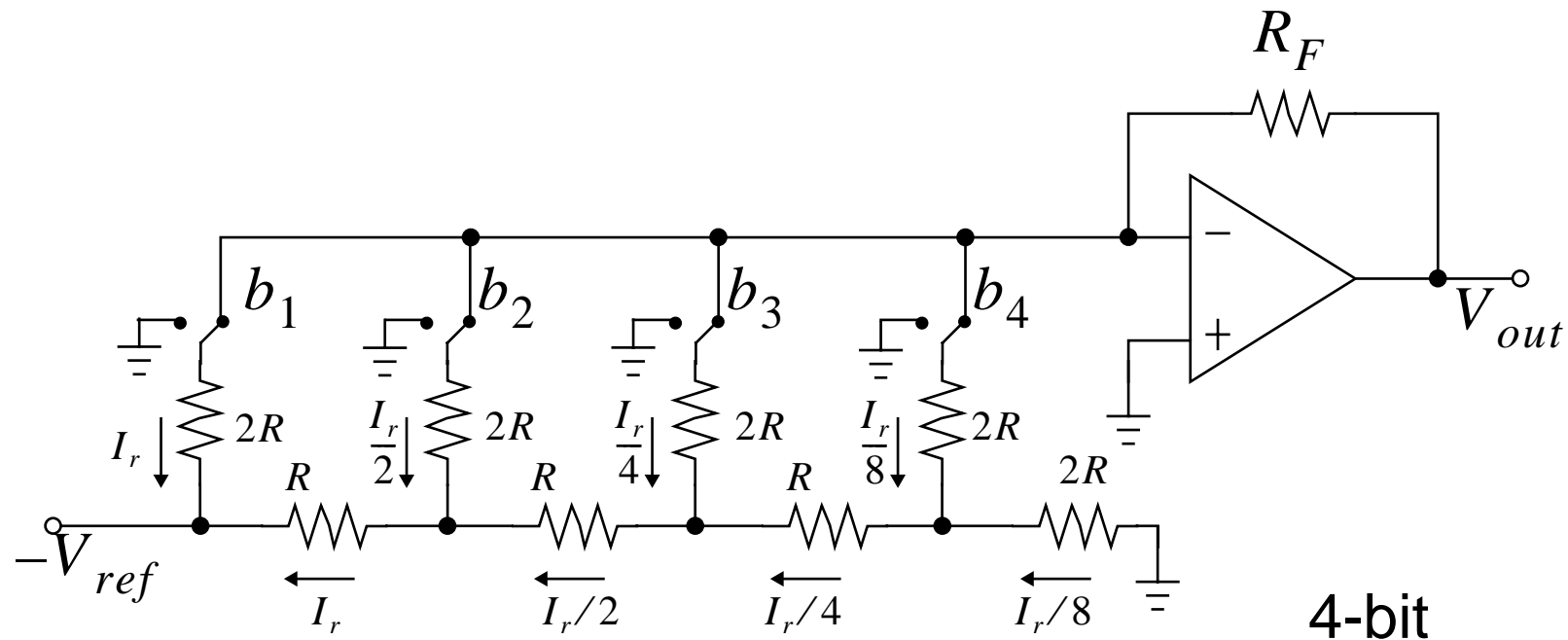$$R_3 = 2R \parallel R'_3 = R$$

(4)

- Small size, good matching (only R and 2R)
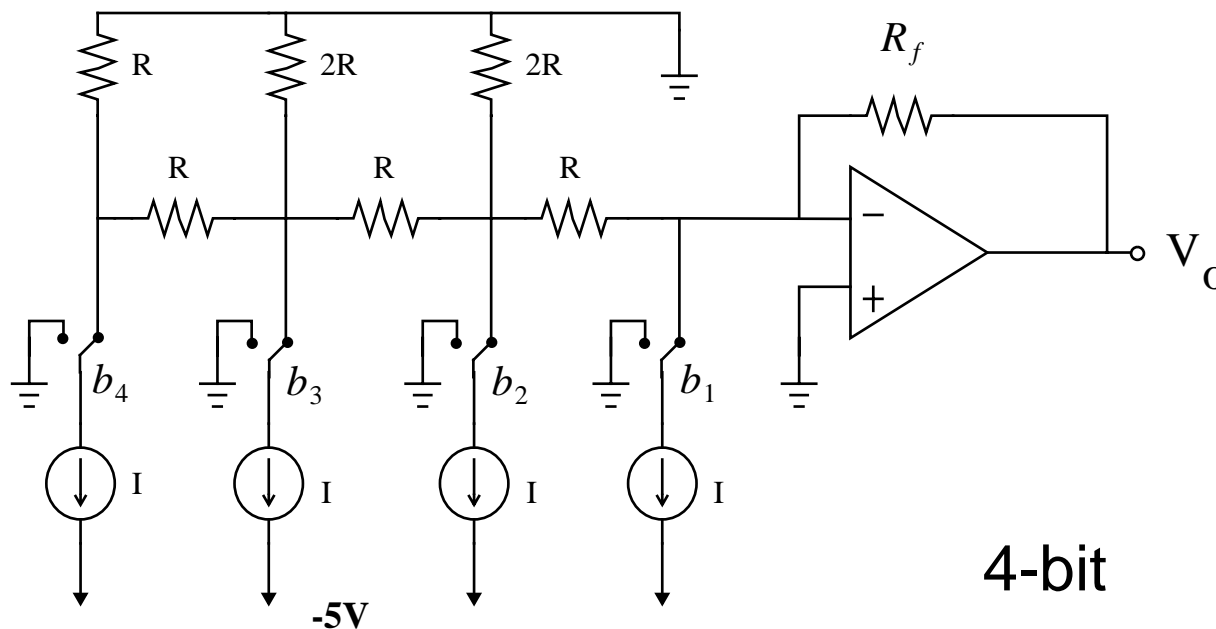
R-2R Based Resistor Ladders

- Example D/A converter

4-bit

- Currents through the switches are scaled
- Should scale switch sizes for good accuracy
- No node voltage changes except for output —> fast

R-2R Based Resistor Ladders

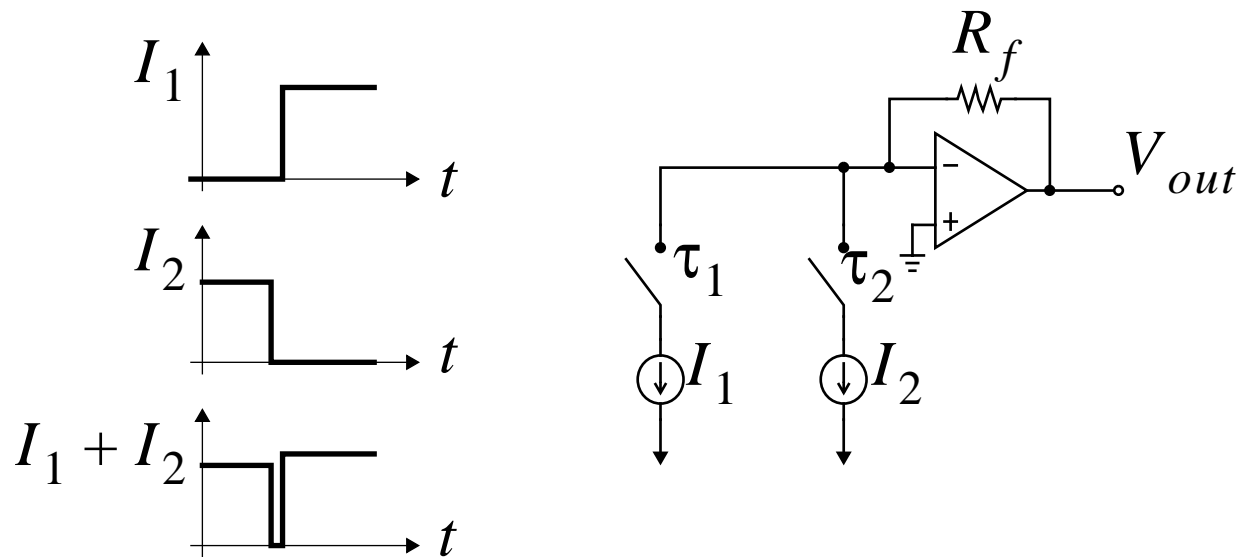- Slower circuit having *equal* current through switches

4-bit

- Node voltages change — slower circuit
- No need to scale switch sizes (smaller size)

Glitches

- Different delays for switching the different currents
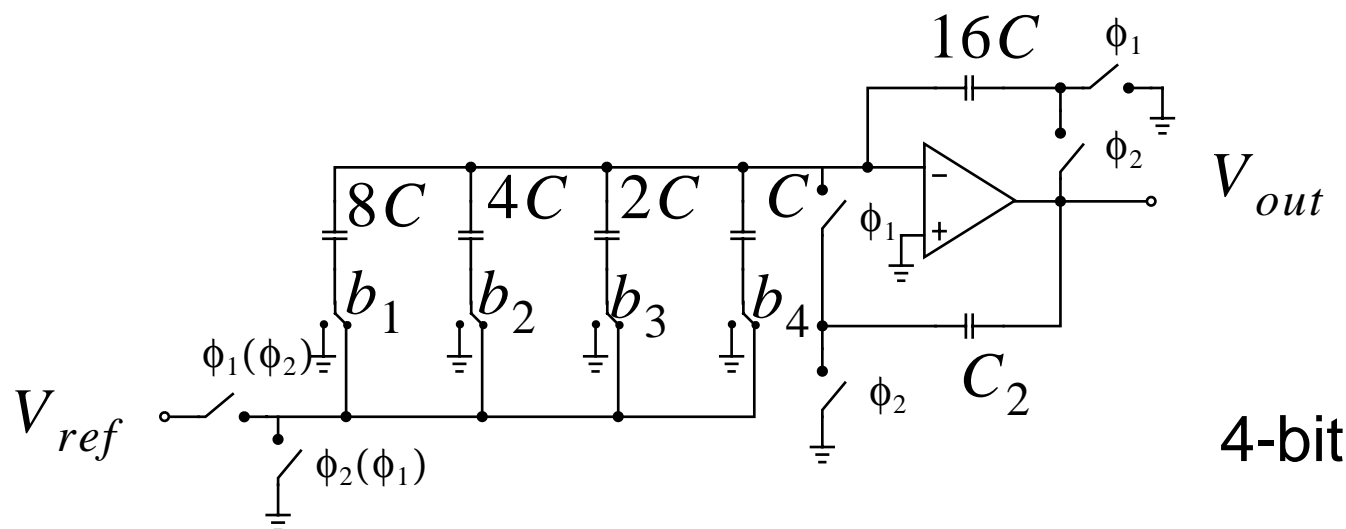- MSB change often worst case

- Glitches can be minimized by limiting the bandwidth but that slows down circuit

- Use thermometer code to reduce glitches

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Charge-Redistribution SC D/A's

- Programmable SC gain amplifier.

- Sign bit realized by interchanging input phases
- Carefully clock-waveforms required to minimize voltage dependency of clock-feed-through.
- Digital codes should be changed when input side of capacitors are connected to ground. Requires extra digital complexity.
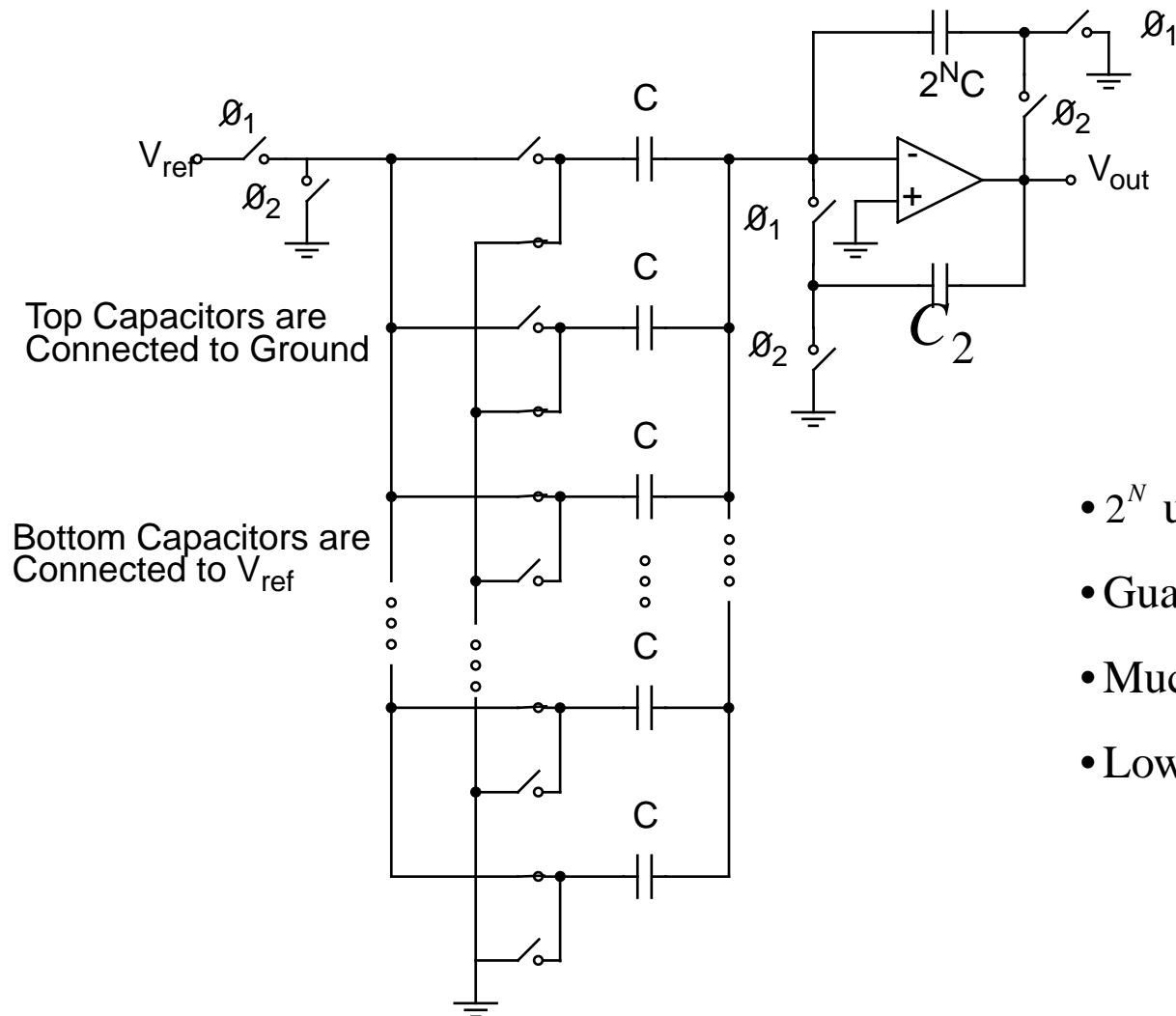
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Thermometer D/A Converters

Decimal	Binary			Thermometer Code						
	b_1	b_2	b_3	d_1	d_2	d_3	d_4	d_5	d_6	d_7
0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	0	0	0	1
2	0	1	0	0	0	0	0	0	1	1
3	0	1	1	0	0	0	0	1	1	1
4	1	0	0	0	0	0	1	1	1	1
5	1	0	1	0	0	1	1	1	1	1
6	1	1	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
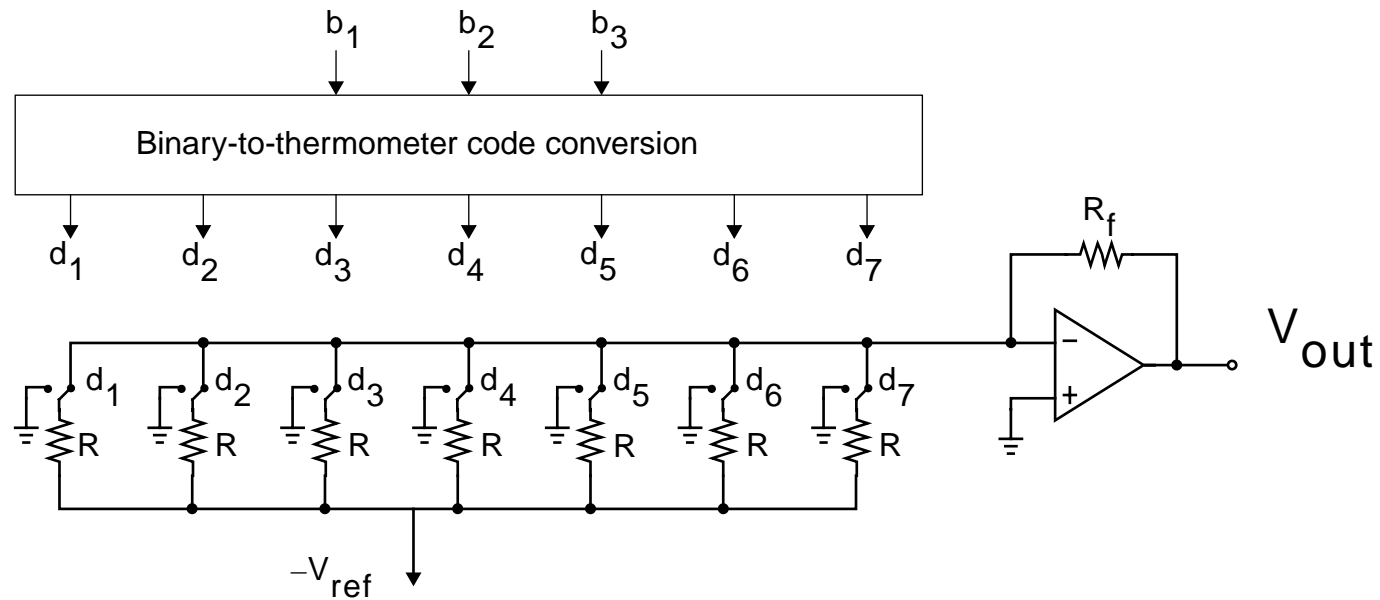
Thermometer Code D/A Converter

- 2^N unit sized caps
- Guaranteed monotonic
- Much lower glitching
- Low DNL

Top Capacitors are Connected to Ground

Bottom Capacitors are Connected to V_{ref}

Current-Mode D/A's
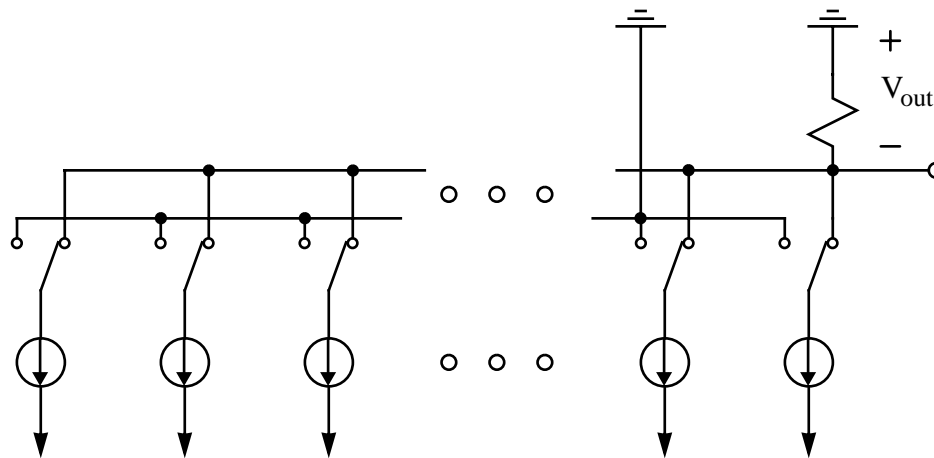
- Thermometer-code

- High-speed, output feeds directly to resistor

- Important that delay to all the switches are equal.

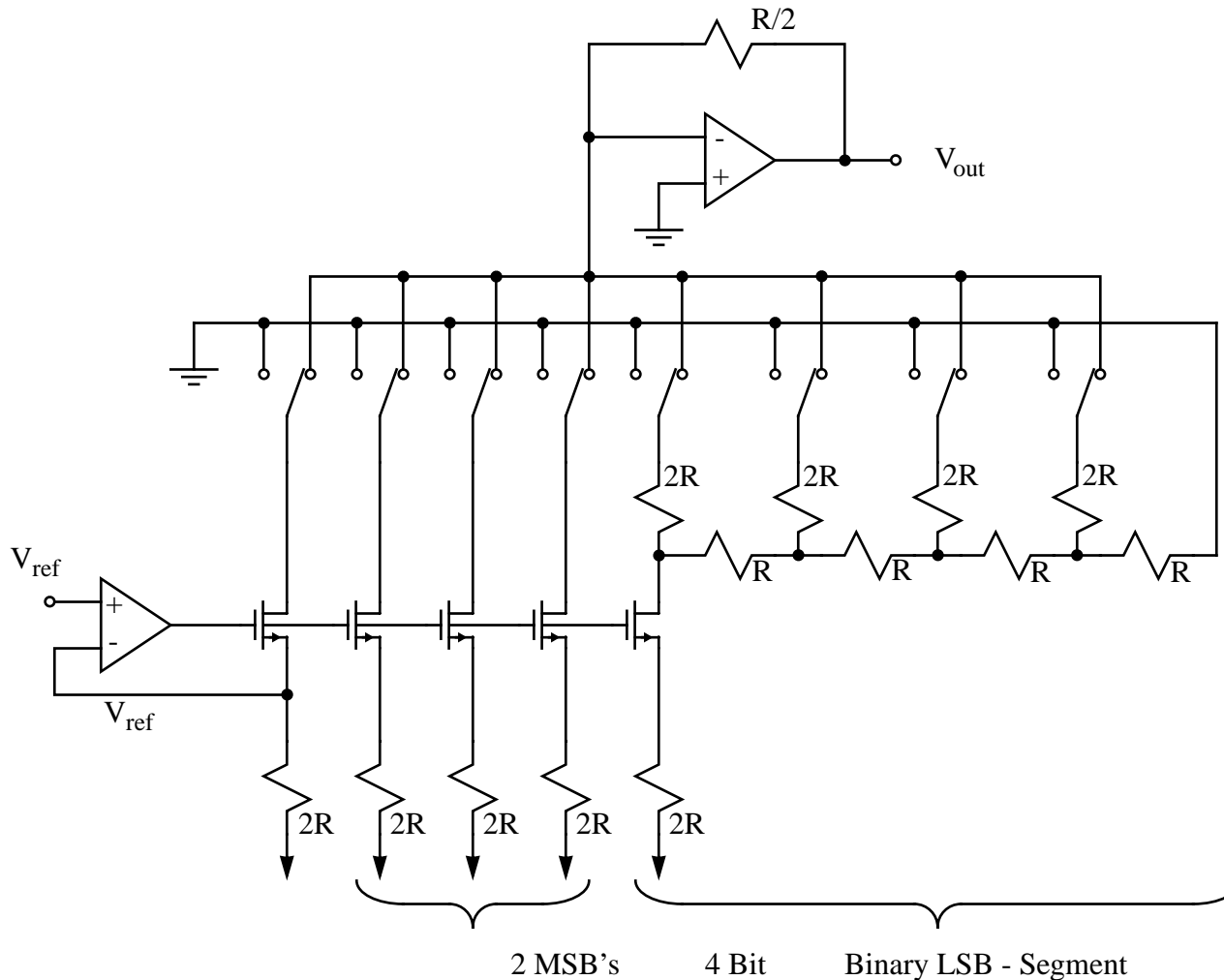- Overlapped clocks much better than having non-overlapped clocks.
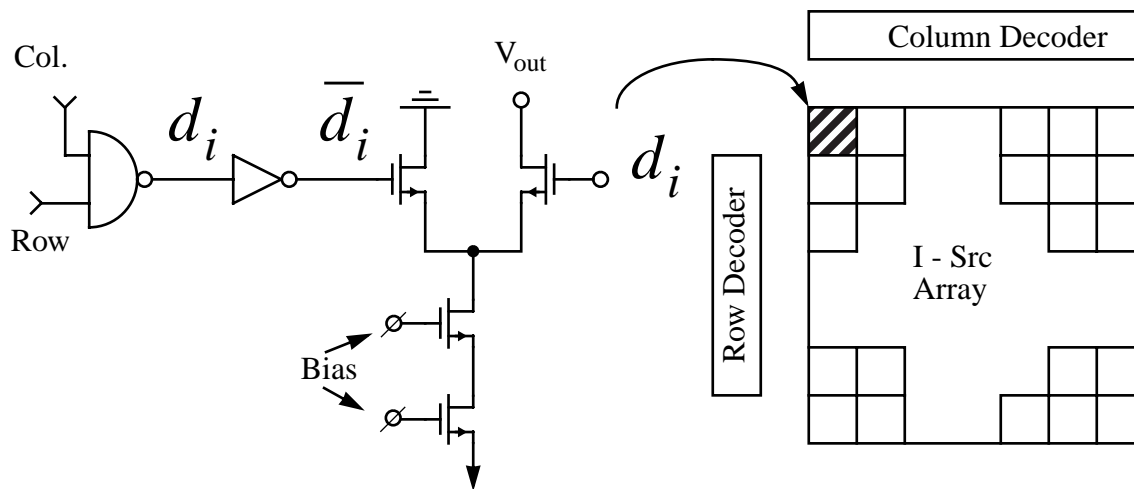
Current-Steered D/A [Colles, 88]

- Operates as cascode current sources.

- For max speed, keep voltage swing at source of Q1 small (just turned off)

- Switching feed-through from the digital input enhances switching speed.
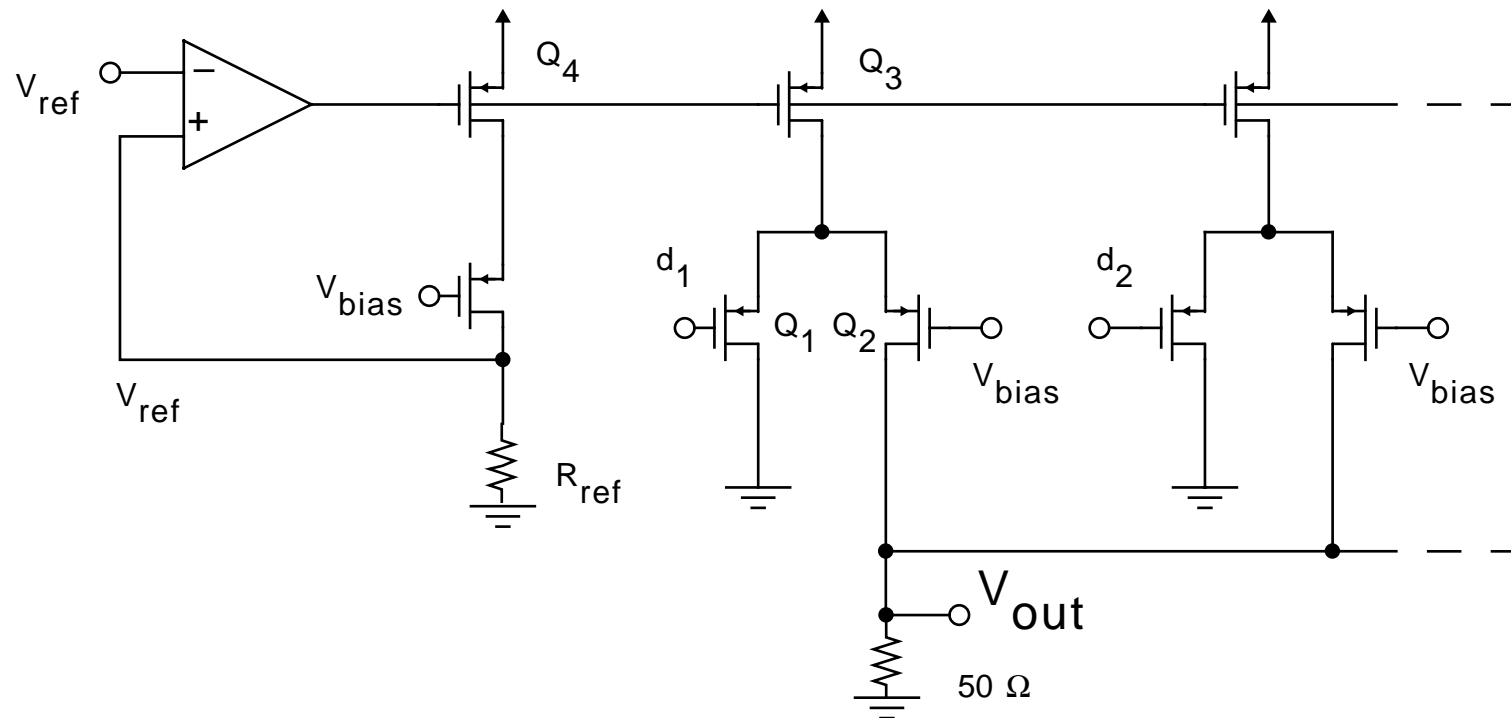
Segmented D/A

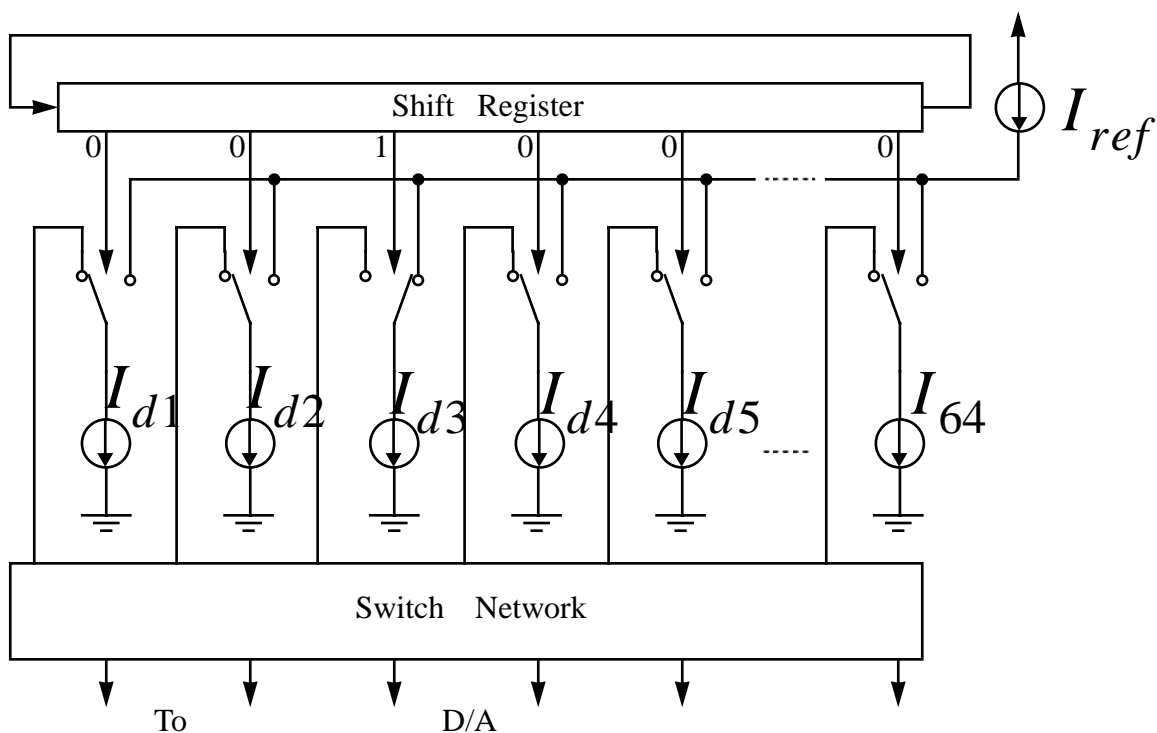- Schoeff, 79; Saul, 85; Grebene, 84

- Combine thermometer and binary

- Accuracy needed for LSB reduced

- Glitches reduced

- Very popular

2 MSB's   4 Bit   Binary LSB - Segment

Dynamically-Matched Current Sources
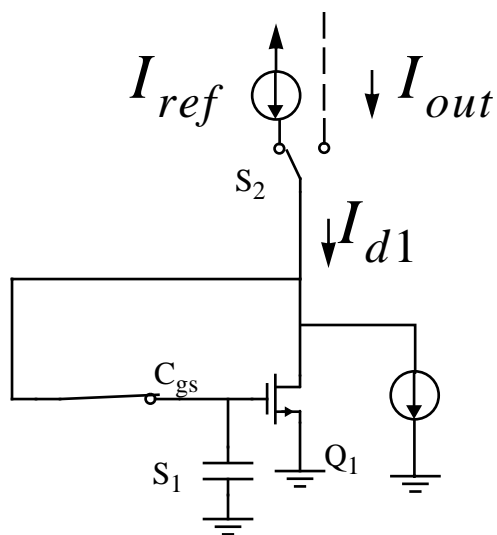
- Schouwenaar, 88

- Each current source is calibrated with a single reference

- 64 used so D/A can continue operating

- Achieved 92 dB SNDR, and 20 mW with 3V.
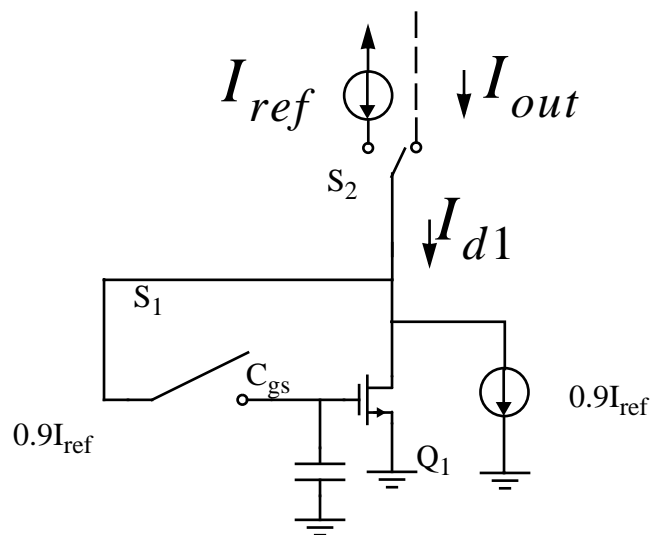
- Used for audio application

- Dynamic technique with current switching for realizing very well-matched current sources

- Up to 16 bit accuracy

Dynamically-Matched Current Sources

Calibration

Regular Usage

- Current source 0.9I added so a low gm device used (W/L equal to 10/75)

- Re-calibrate before leakage causes 0.5LSB error

- Minimize clock-feedthrough and charge-injection by having capacitance C_{gs} and bias voltage V_{GS} large

- Implies voltage error causes less current deviation.