11.1 Bandgap References

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Compliment to SeungHyun Lee

What is required of a reference?

- **DC voltage or current that is**

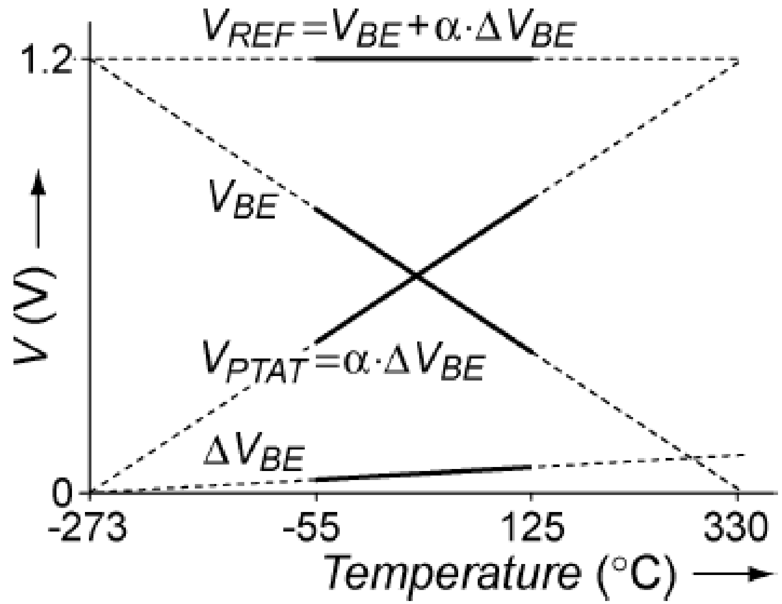
1. **Independent of the Supply variation**
   - **e.g.: V_{CC}: 2.7V → 3.0V**

2. **Independent of the Temperature variation**
   - **e.g.: T: -20°C → 80°C**

3. **Independent of the process variation**
   - **e.g.: β of BJTs: ± 30%**

Temperature-Independent References

- $V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$ (V_1 is Proportional To Absolute Temperature, PTAT, and V_2 Complementary TAT, CTAT)



Temperature dependency of the key voltages in the sensor.

[M. Pertijs, JSSC, 2005]

Negative-TC Voltage

- **The base-emitter voltage of a bipolar transistor V_{BE} exhibits a negative TC.**

- **For a bipolar device, $I_C = I_S \exp(\frac{V_{BE}}{V_T})$, where $V_T = \frac{kT}{q}$ and I_S is proportional to $\mu_k T n_i^2$.**

- **Temperature dependence: $\mu \propto \mu_0 T^{m}$, where $m \approx -\frac{2}{3}$ and $n_i^2 \propto T^3 \exp[\frac{-Eg}{kT}]$, where $E_g \approx 1.12$ eV is the bandgap energy of silicon.**

- **Thus, $I_s = bT^{4+m} \exp\frac{-Eg}{kT}$ (b is a proportional factor).**

Negative-TC Voltage

- **Writing $V_{BE} = V_T \ln(\frac{I_C}{I_S})$, and assuming for now that I_C is held constant,**

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T}$$

- **Since**

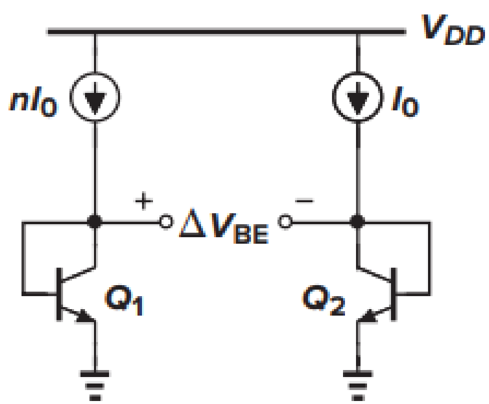
$$\frac{\partial I_S}{\partial T} = b(4+m)T^{3+m} \exp\frac{-E_g}{kT} + bT^{4+m}\left(\exp\frac{-E_g}{kT}\right)\left(\frac{E_g}{kT^2}\right) \Rightarrow \frac{V_T}{I_S}\frac{\partial I_S}{\partial T} = (4+m)\frac{V_T}{T} + \frac{E_g}{kT^2}V_T$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T} = \frac{V_{BE} - (4+m)V_T - E_g/q}{T}$$

Thus, with V_{BE} ≈ 750 mV and T = 300K, $\partial V_{BE} / \partial T \approx -1.5$ mV/K

Positive-TC Voltage

- **The difference between two base-emitter voltages, ΔV_{BE} exhibits a positive-TC.**

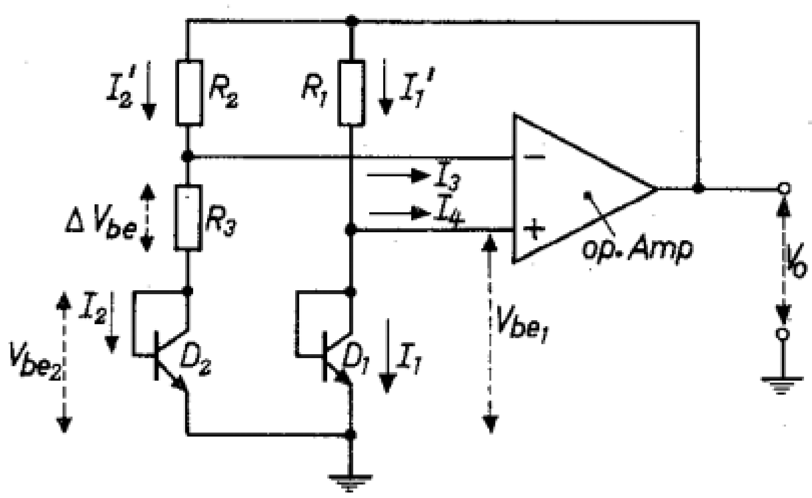


$$\begin{aligned}
\Delta V_{BE} &= V_{BE1} - V_{BE2} \\
&= V_T \ln \frac{nI_0}{I_{S1}} - V_T \ln \frac{I_0}{I_{S2}} \\
&= V_T \ln n \\
\frac{\partial \Delta V_{BE}}{\partial T} &= \frac{k}{q} \ln n
\end{aligned}$$

- **To compensate for -1.5 mV/K, ln n ≈ 17.2, hence n ≈ 2.95x10^7!!**

Bandgap Reference

- **Large n can be mitigated if ΔV_{BE} is "Amplified" before it is added to V_{BE} .**



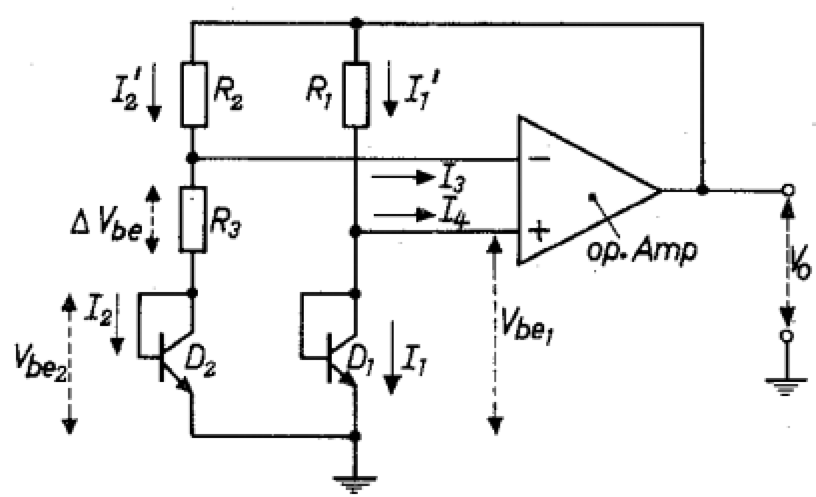
$$V_{out} = V_{BE2} + \frac{V_T \ln n}{R_3}(R_3 + R_2)$$
$$= V_{BE2} + (V_T \ln n)\left(1 + \frac{R_2}{R_3}\right)$$

[K. KUIJK, JSSC, 1973]

Bipolar Bandgap Reference

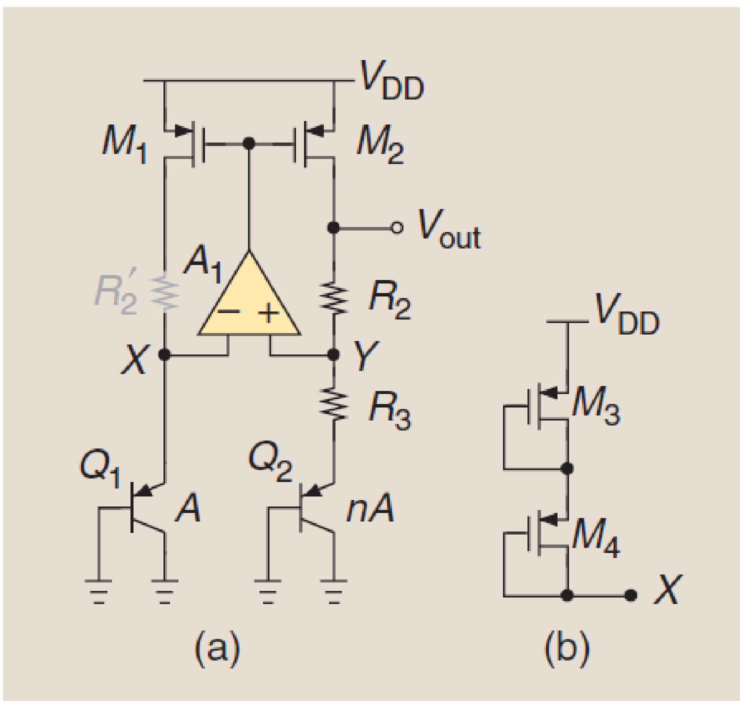
Three issues

1. **Gain-power-stability trade-offs**
2. **NPN bipolar transistors**
3. **Op-amp offset**



CMOS bandgap Reference

- Replace resistors with controlled current sources.
- Bipolar transistors are implemented as PNP structures.
- Large n & non-unity ratio between I_{E1} and I_{E2}.

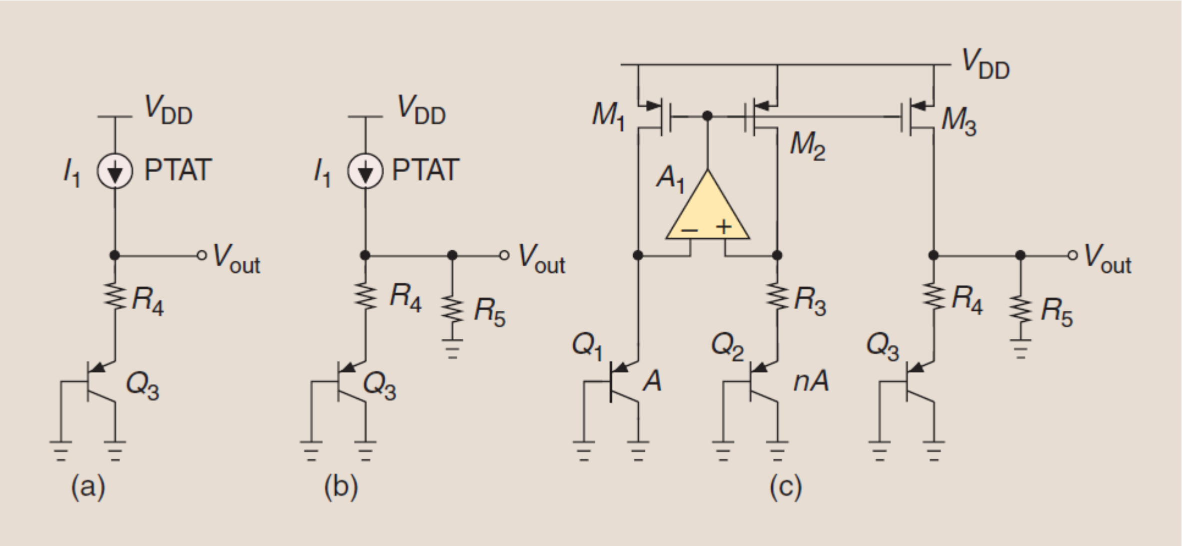


[B. Razavi, IEEE SSC Magazine , 2016]

Low-Voltage Bandgap Reference (1)

- **In (a), V_{out} is still around 1.25V.**
- **In (b), V_{out} is arbitrarily small, about 700-800mV.**

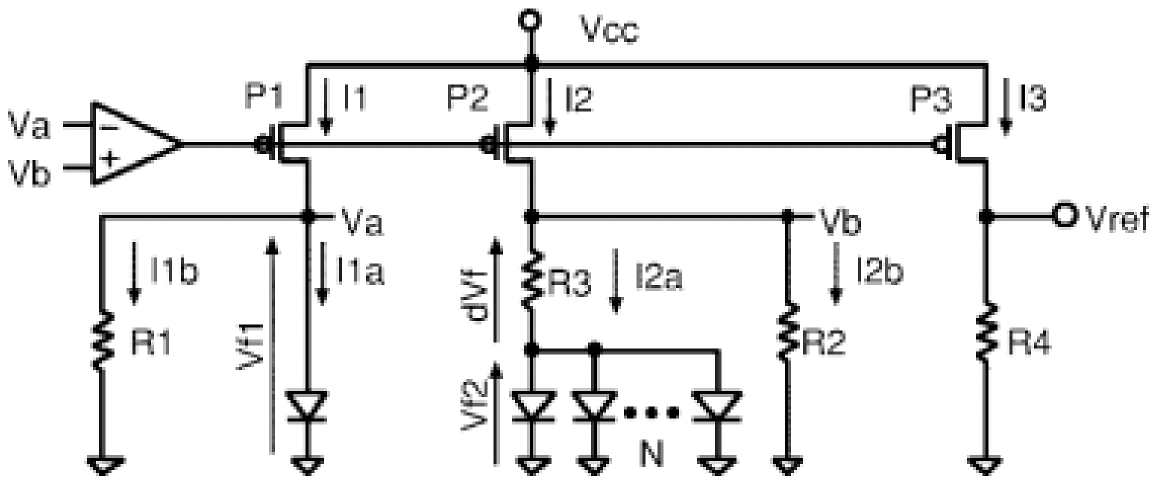
$$V_{out} = \frac{R_5}{R_5 + R_4}(R_4 I_1 + V_{BE3}),$$



[B. Razavi, IEEE SSC Magazine , 2016]

Low-Voltage Bandgap Reference (2)

- **Use of shunt resistors**



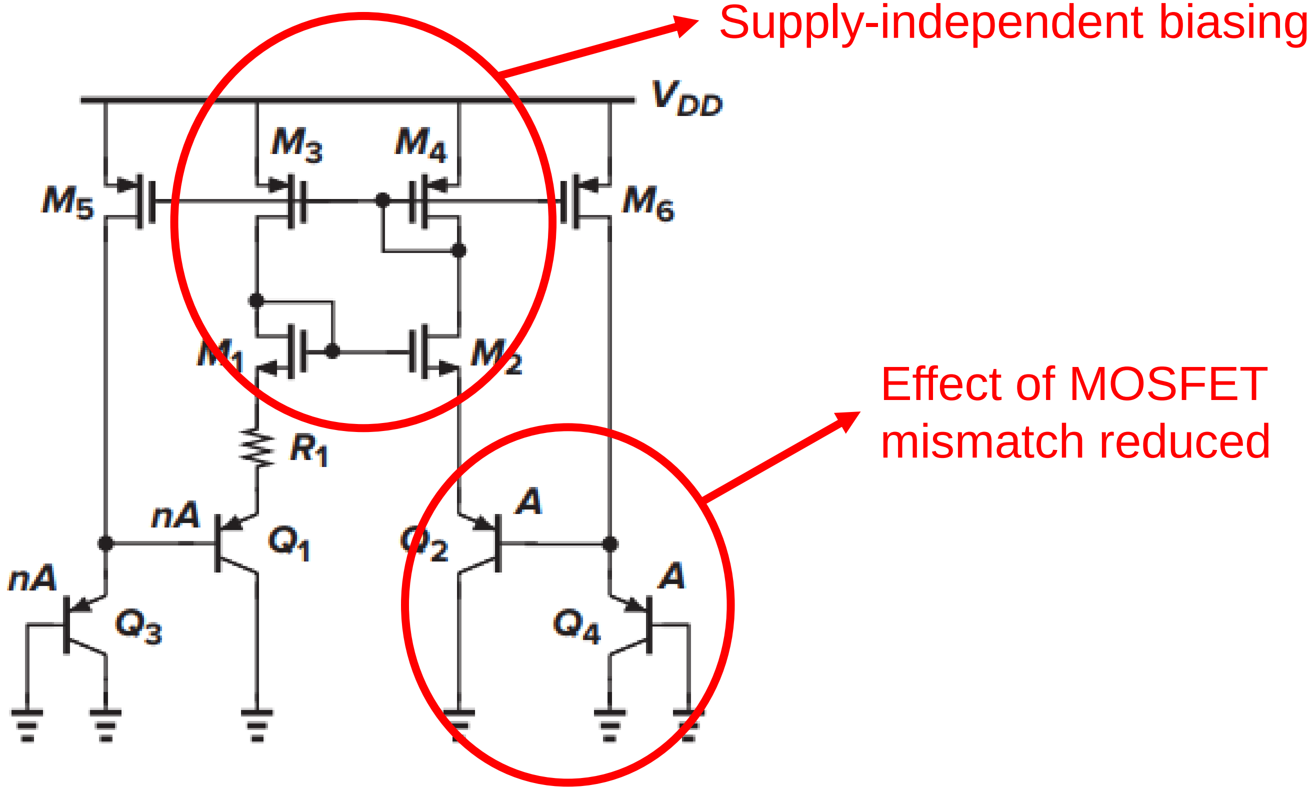
$$V_{\mathrm{ref}} = R4\left(\frac{V_{f1}}{R2} + \frac{dV_f}{R3}\right) \equiv V_{\mathrm{ref\_prop}}$$

$$V_{\mathrm{ref\_prop}} = \frac{R4}{R2} V_{\mathrm{ref\_conv}}$$

[H. Banda, JSSC, 1999]

PVT-Tolerant Bandgap Reference

- **Effect of device mismatches is reduced.**



[T. Brooks, ISSCC , 1994]

Compatibility with CMOS Technology

- **p+ diffusion inside n-well ➔ Emitter**
- **n-well ➔ Base**
- **p- substrate ➔ Collector**

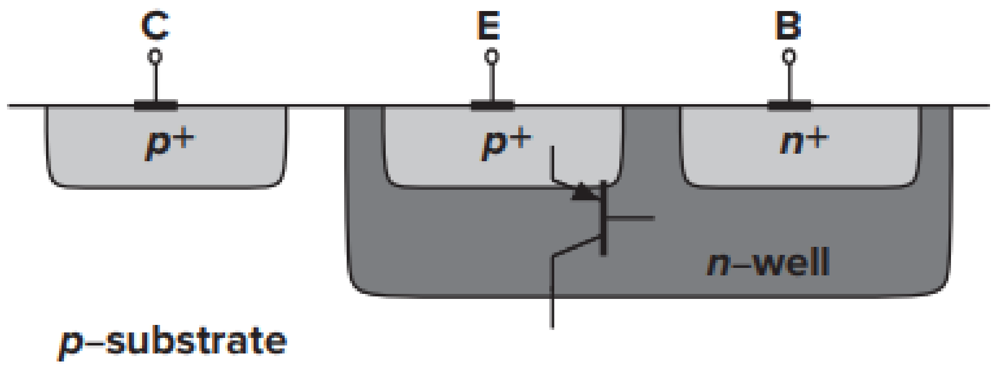
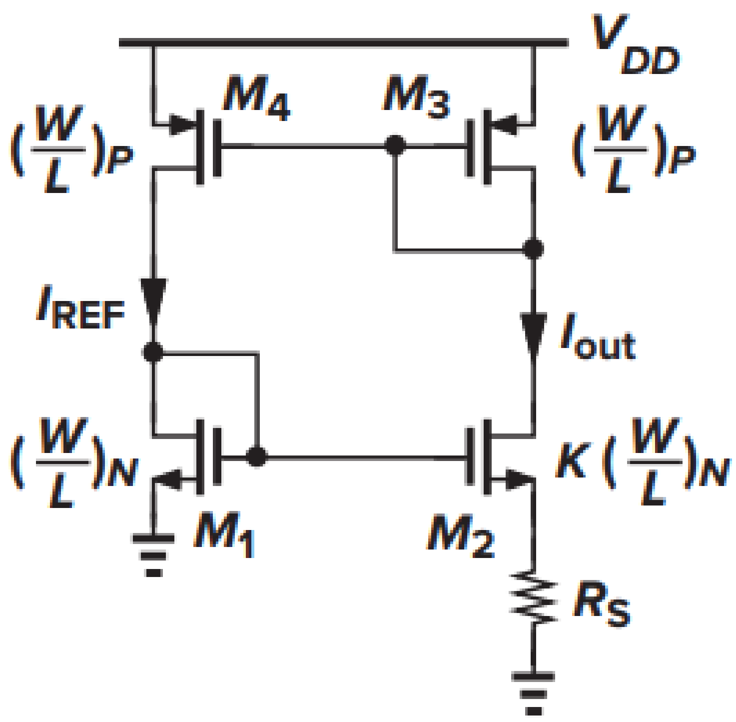


Figure 12.10 Realization of a *pnp* bipolar transistor in CMOS technology.

[B. Razavi, Design of Analog CMOS Integrated Circuits]

Current Reference

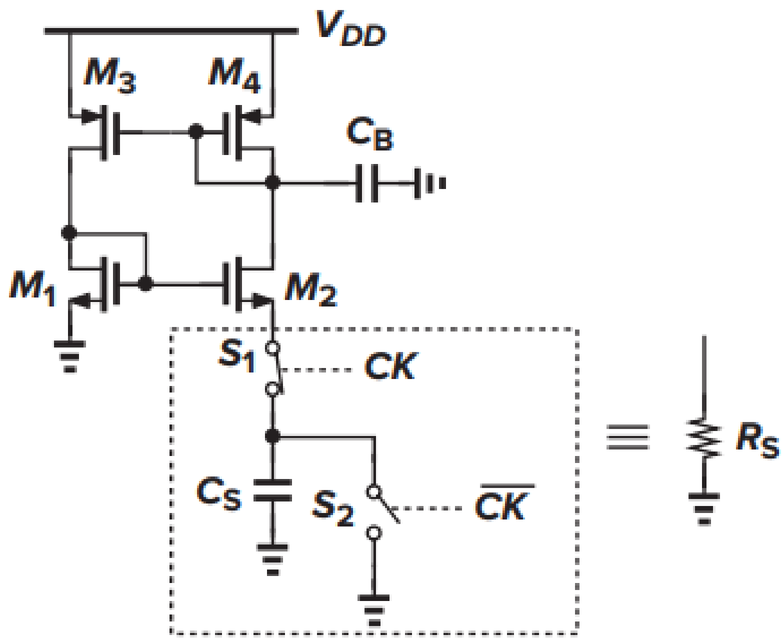
- **Use of Widlar Current Mirror.**
- **Current I_{out} is independent of the supply voltage.**



$$I_{out} = \frac{2}{\mu_n C_{ox}(W/L)_N} \cdot \frac{1}{R_S^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

Current Reference with SC Resistor

- ***Rs*** **can be replaced by a switched-capacitor equivalent: Temperature insensitivity.**



$$R_s = \frac{1}{f C_s}$$

References

- **K. E. Kujik, “A precision reference voltage source,” IEEE J. Solid-State Circuits, vol. 8, pp. 222–226, June 1973.**
- **H. Banba, H. Shiga, A. Umezawa, and T. Miyaba, “A CMOS bandgap reference circuit with sub-1-V operation,” IEEE J. SolidState Circuits,**
- **B. Razavi, “The bandgap reference,” IEEE Solid-State Circuits Mag., vol. 8, pp. 9–12, Summer 2016.**
- **B. Razavi, "Design of Analog CMOS Integrated Circuits", *Tata McGraw Hill*, 2002. , pp.509-533**
- **T. Brooks and A. L. Westwisk, “A Low-Power Differential CMOS Bandgap Reference,” ISSCC Dig. of Tech. Papers, pp. 248–249, February 1994.**