Static and Dynamic Translinear Circuits

Bradley A. Minch

Mixed Analog-Digital VLSI Circuits and Systems Lab
Cornell University
Ithaca, NY 14853–5401

minch@ece.cornell.edu

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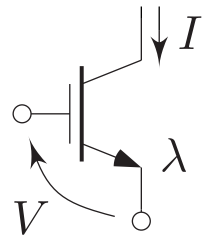
Translinear Devices and Circuits: What's In A Name?

A translinear element is one whose incremental transconductance gain is linear in its output current



$$I = \lambda I_{\mathrm{s}} e^{V/U_{\mathrm{T}}} \quad \Longrightarrow \quad g_{\mathrm{m}} = \frac{\partial I}{\partial V} = \underbrace{\lambda I_{\mathrm{s}} e^{V/U_{\mathrm{T}}}}_{I} \cdot \frac{1}{U_{\mathrm{T}}} = \frac{I}{U_{\mathrm{T}}}$$

The word translinear is also meant to convey the notion of bridging the gap between the familiar world of linear circuit design and the largely uncharted territory of nonlinear circuit design.

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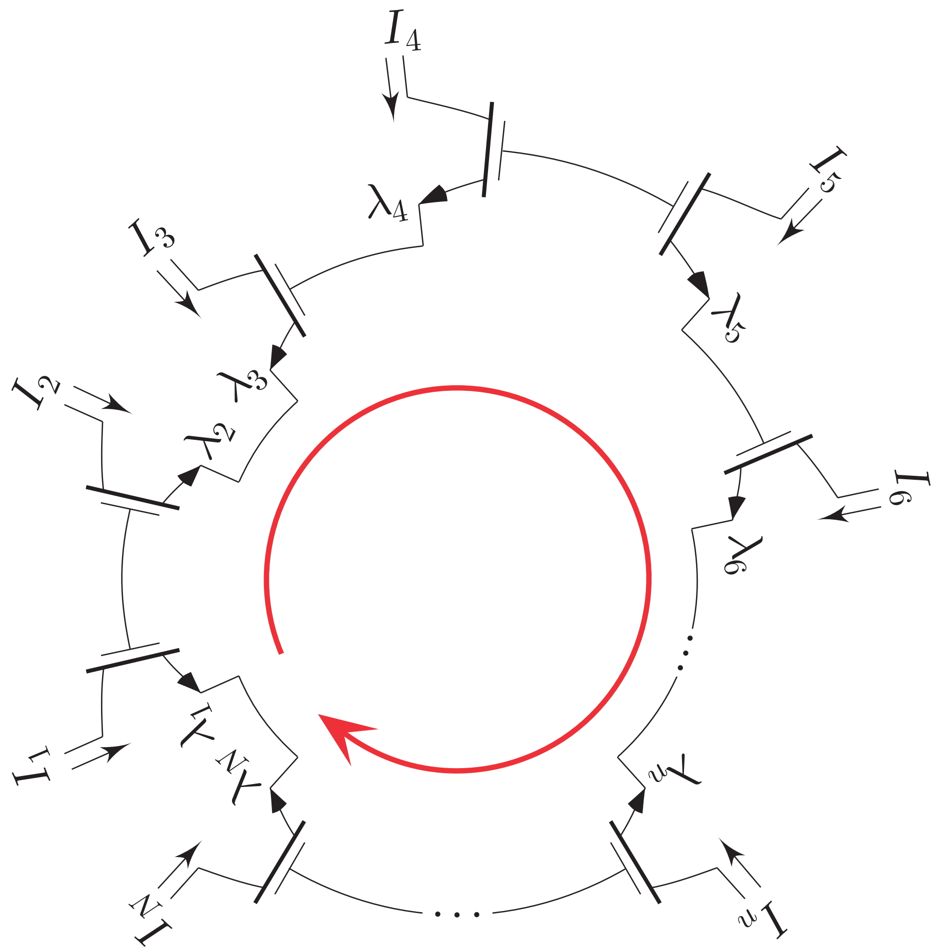
The Translinear Principle

In a closed loop of junctions comprising an equal number of clockwise and counterclockwise elements, the product of the current densities flowing through the counterclockwise elements is equal to the product of the current densities flowing through the clockwise elements.

$$\prod_{n\in\mathrm{CW}} \frac{I_n}{\lambda_n} = \prod_{n\in\mathrm{CCW}} \frac{I_n}{\lambda_n}$$



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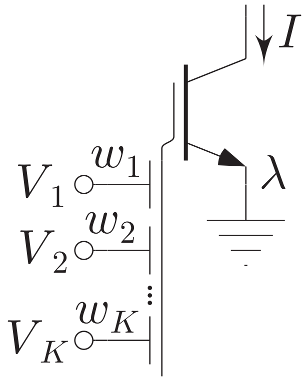
The Ideal Multiple-Input Translinear Element

The ideal multiple-input translinear element (MITE) produces an output current given by

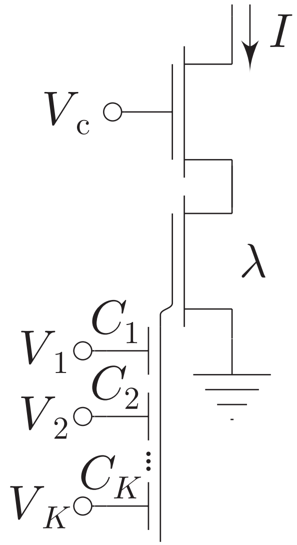
$$I = \lambda I_{\mathrm{s}} e^{(w_1 V_1 + \cdots + w_K V_K)/U_{\mathrm{T}}}$$

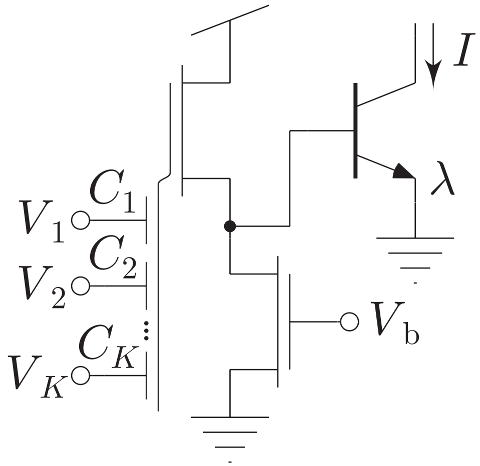


where

I_{s}	pre-exponential scaling current
λ	dimensionless constant scaling I_{s} proportionally
V_k	kth control-gate voltage
w_k	dimensionless positive weight scaling V_k
U_{T}	thermal voltage, kT/q.

Practical Floating-Gate MITE Implementations





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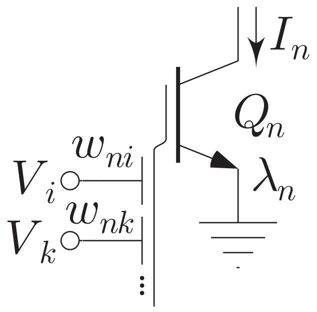
Basic MITE Circuit Stages



$$I_n \propto e^{w_{ni} V_i / U_{\mathrm{T}}} e^{w_{nk} V_k / U_{\mathrm{T}}}$$

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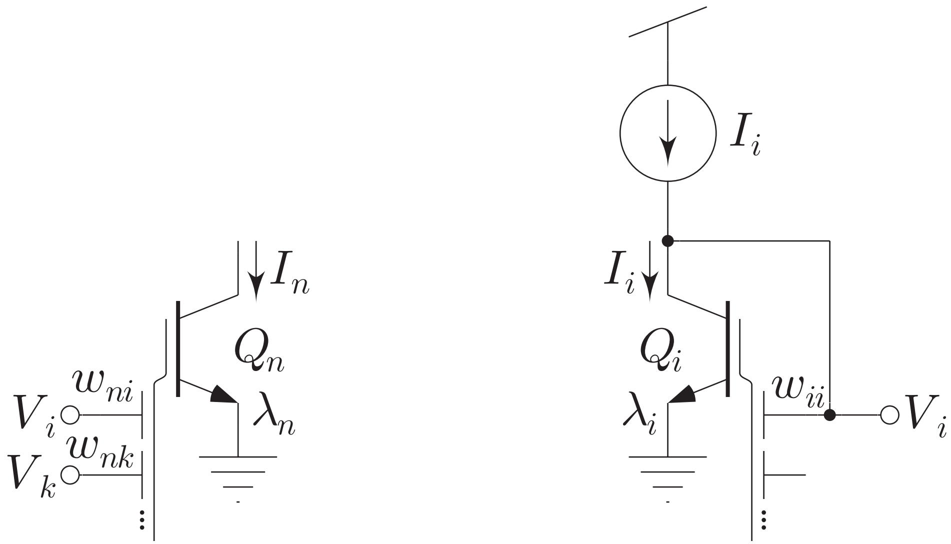

$$I_n \propto e^{w_{ni}V_i/U_\mathrm{T}} e^{w_{nk}V_k/U_\mathrm{T}} \qquad V_i = \frac{U_\mathrm{T}}{w_{ii}} \log I_i - \cdots$$

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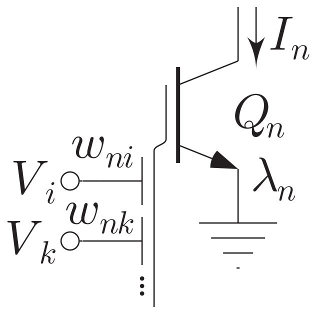

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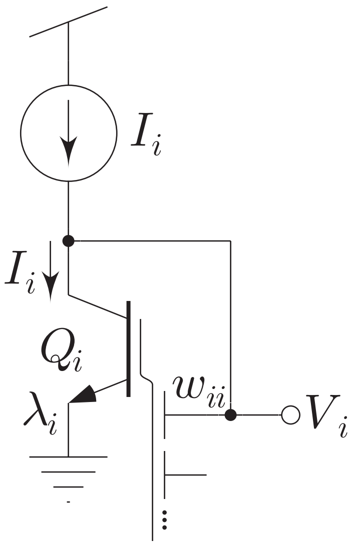
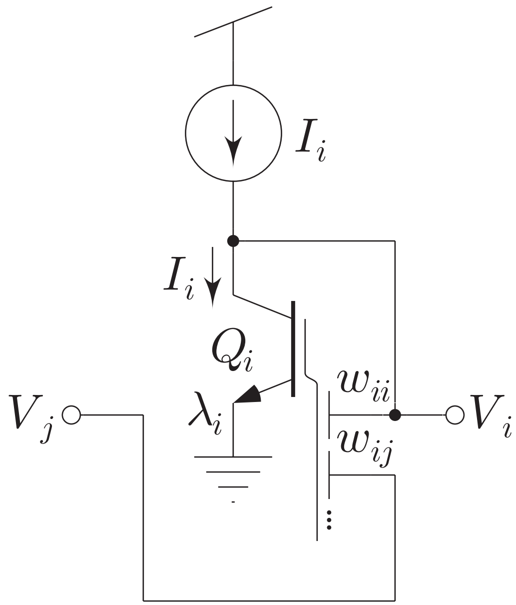


$$V_i = \frac{U_{\mathrm{T}}}{w_{ii}} \log I_i - \cdots$$



$$V_i = \frac{U_{\mathrm{T}}}{w_{ii}} \log I_i - \frac{w_{ij}}{w_{ii}} V_j - \cdots$$

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Elementary MITE Networks

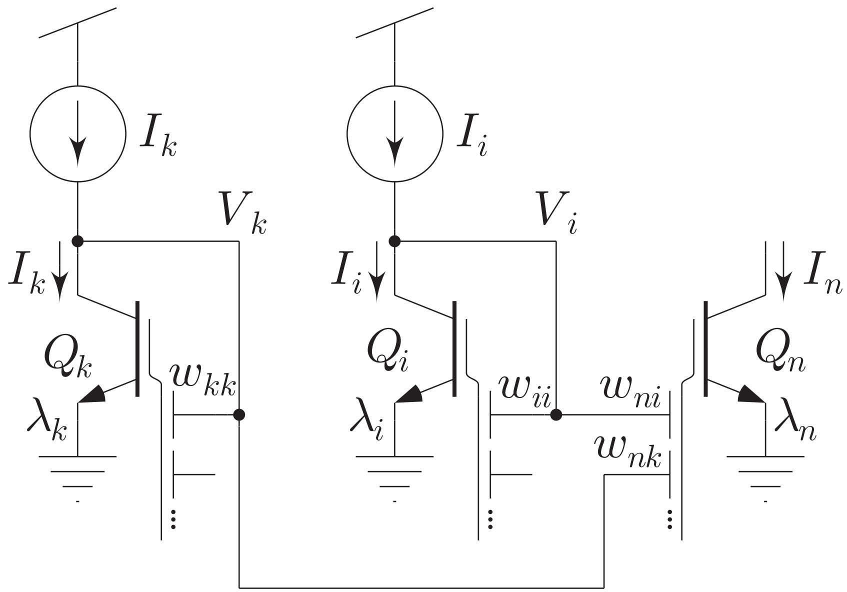
$$I_n \propto e^{w_{ni} V_i / U_\mathrm{T}} e^{w_{nk} V_k / U_\mathrm{T}}$$

$$\Longrightarrow I_n \propto \exp\left(\frac{w_{ni}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{ii}} \log I_i - \cdots\right)\right)$$

$$\times \exp\left(\frac{w_{nk}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{kk}} \log I_k - \cdots\right)\right)$$

$$\Longrightarrow I_n \propto e^{(w_{ni}/w_{ii}) \log I_i} e^{(w_{nk}/w_{kk}) \log I_k}$$

$$\Longrightarrow I_n \propto I_i^{w_{ni}/w_{ii}} \times I_k^{w_{nk}/w_{kk}}$$



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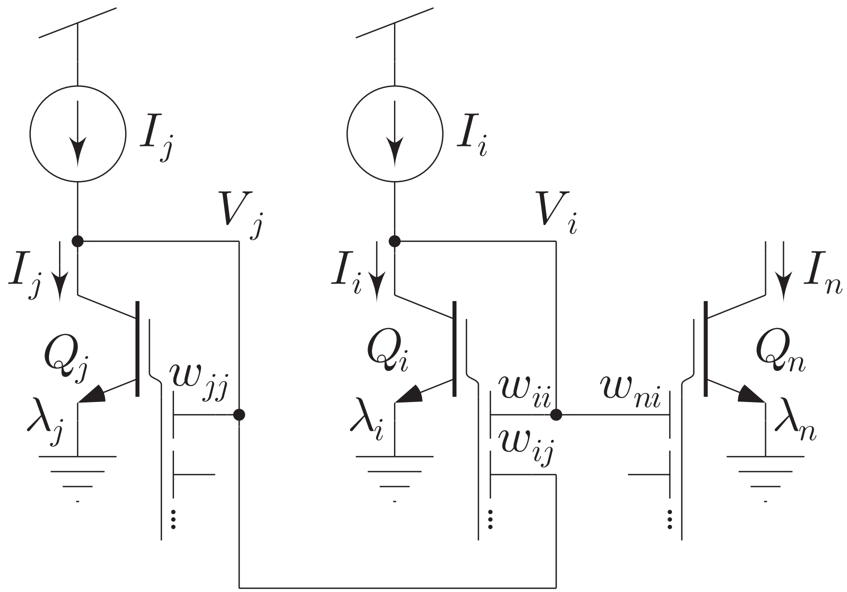
$$\Longrightarrow I_n \propto e^{(w_{ni}/w_{ii})\log I_i} e^{-\left(w_{ni}w_{ij}/w_{ii}w_{jj}\right)\log I_j}$$

$$\Longrightarrow I_n \propto \frac{I_i^{w_{ni}/w_{ii}}}{I_j^{w_{ni}w_{ij}/w_{ii}w_{jj}}}$$



Static MITE Network Synthesis: Square-Root Circuit

Synthesize a square-root circuit described by

$$z = \sqrt{x}, \quad \text{where} \quad x > 0.$$

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$$\frac{I_z}{I_1} = \sqrt{\frac{I_x}{I_1}}$$

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$$\frac{I_z}{I_1} = \sqrt{\frac{I_x}{I_1}} \quad \Longrightarrow \quad I_z = \sqrt{I_x I_1} \quad \Longrightarrow \quad I_z^2 = I_x I_1.$$

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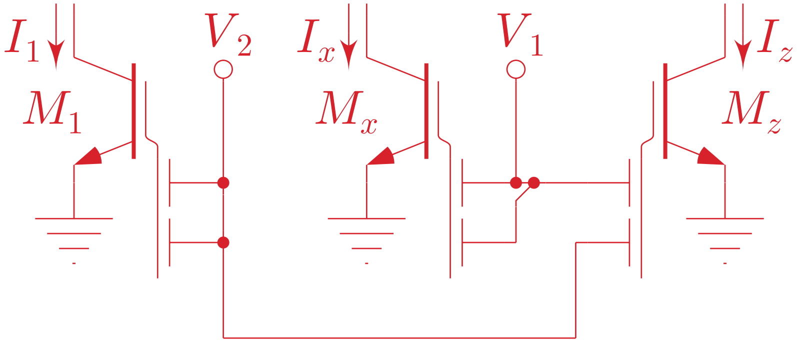

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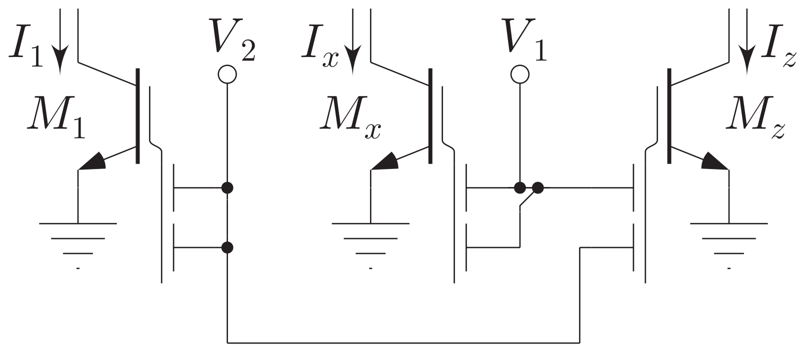

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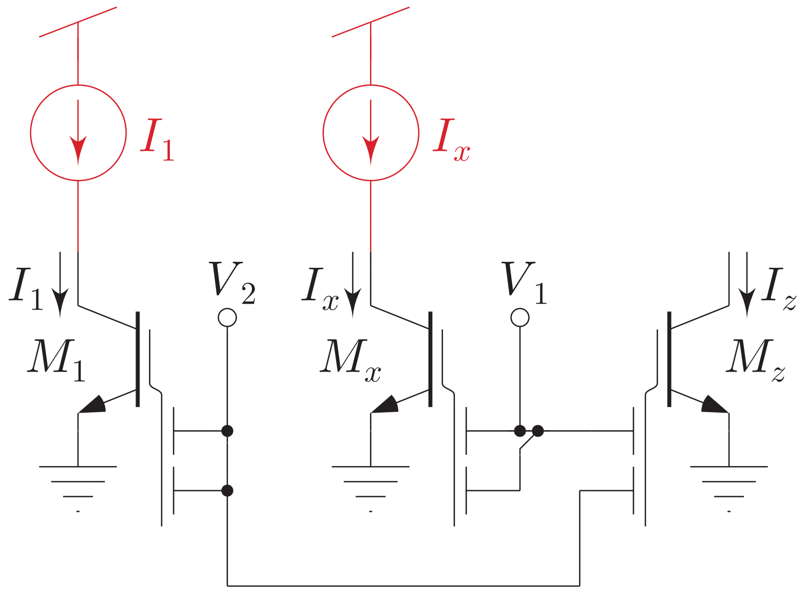

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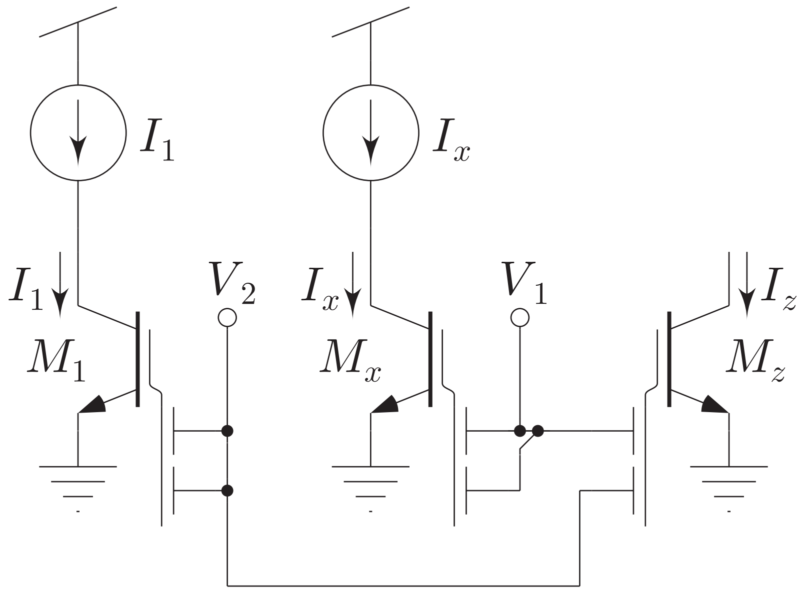

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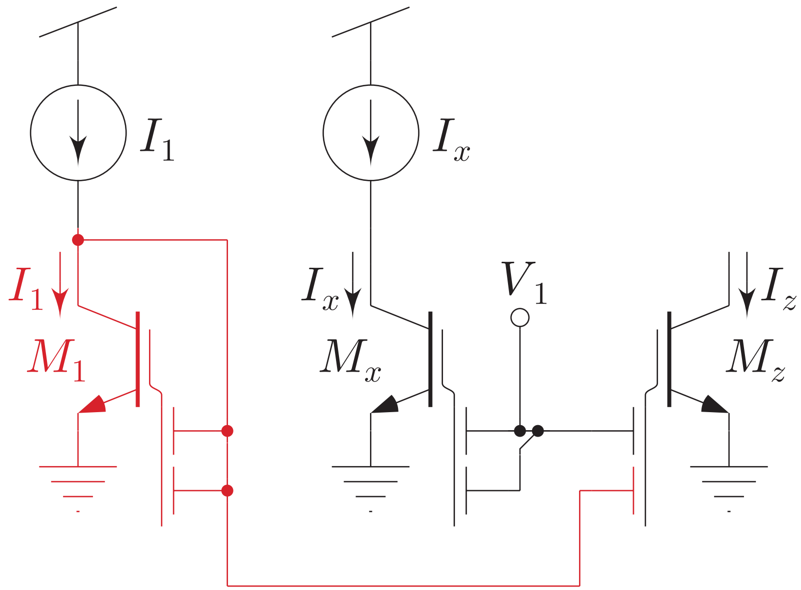

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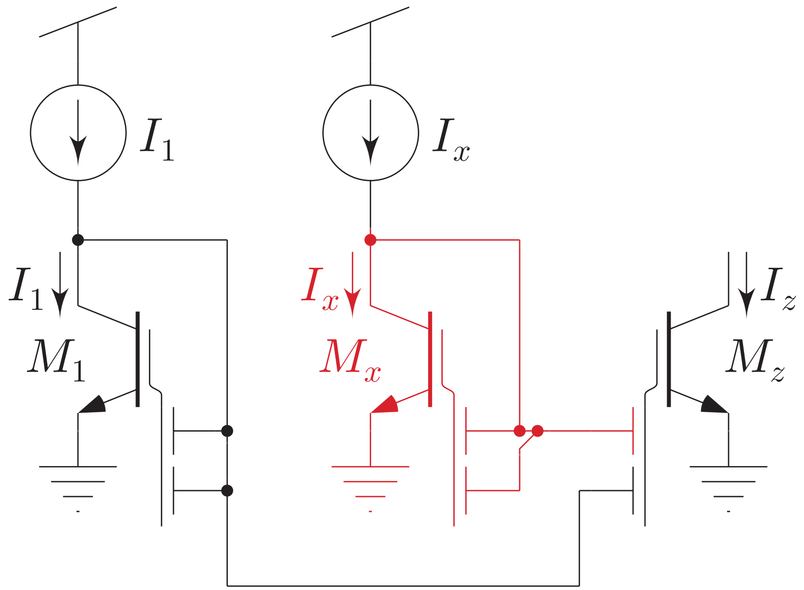

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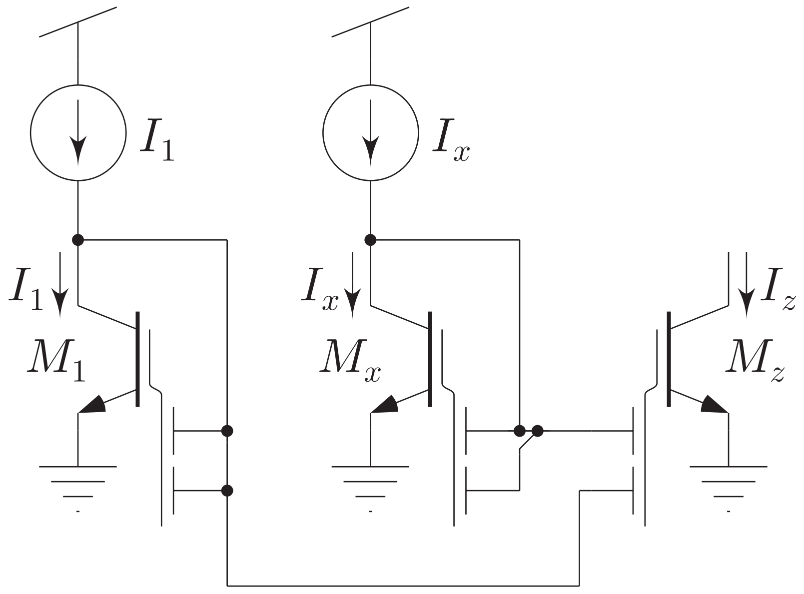
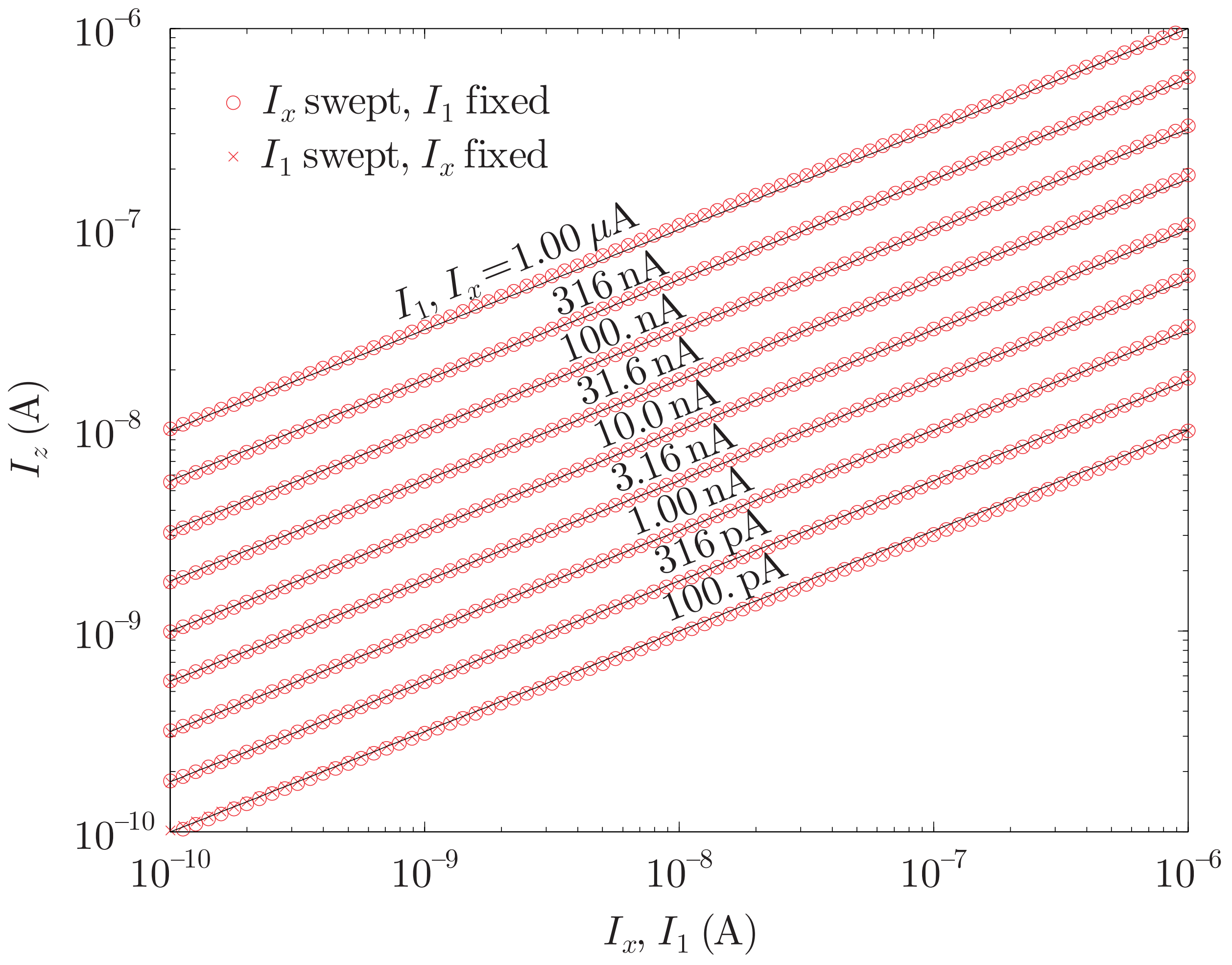


Experimental Measurements: Square-Root Circuit



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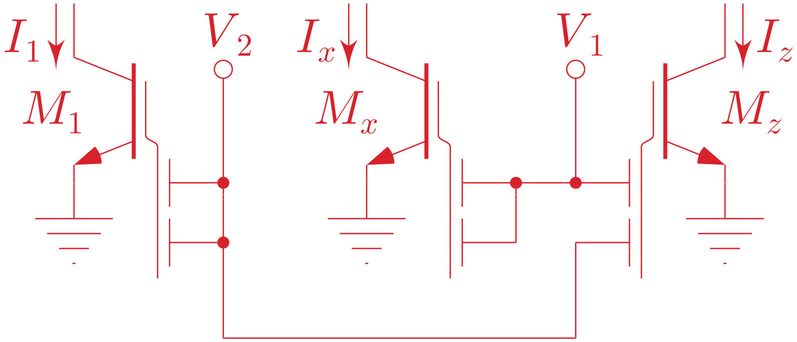

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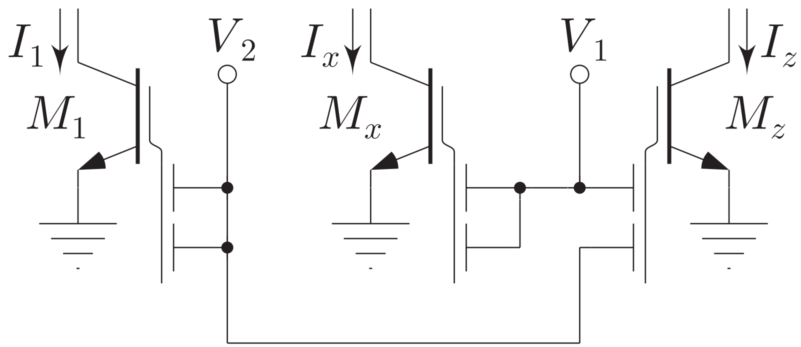

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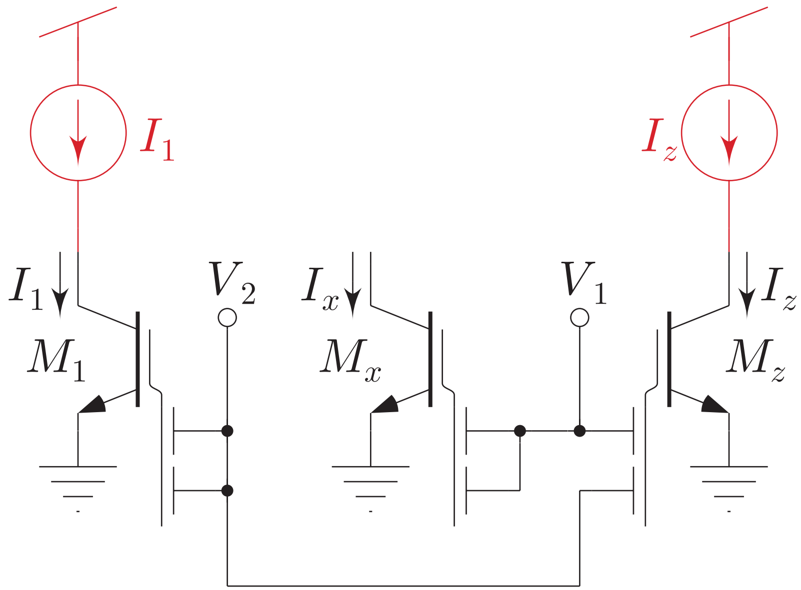

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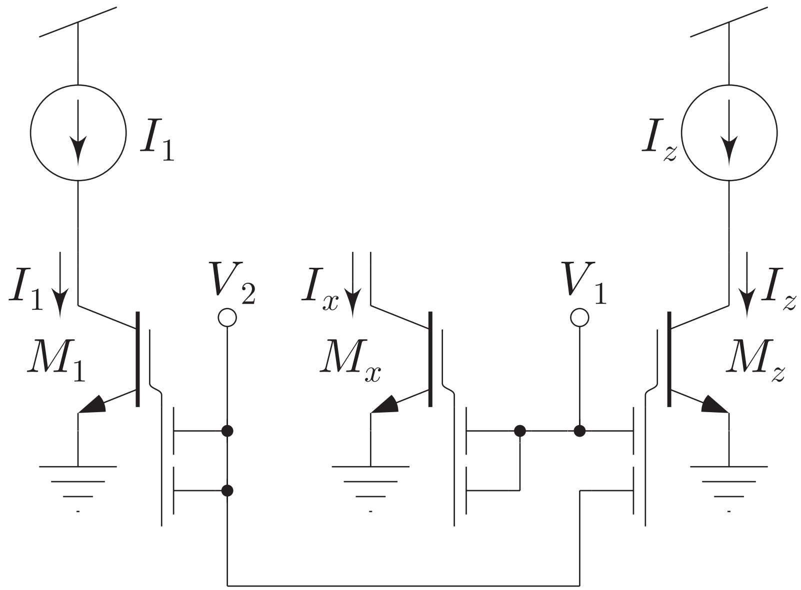

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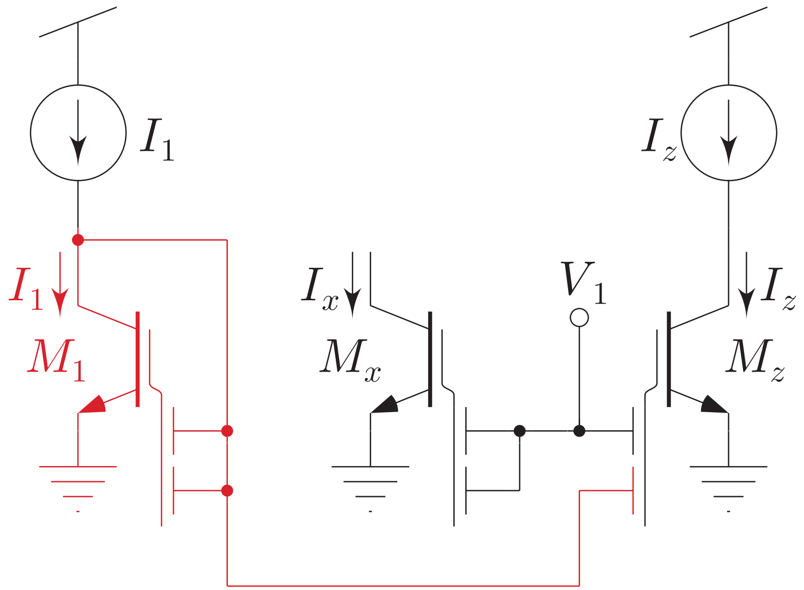

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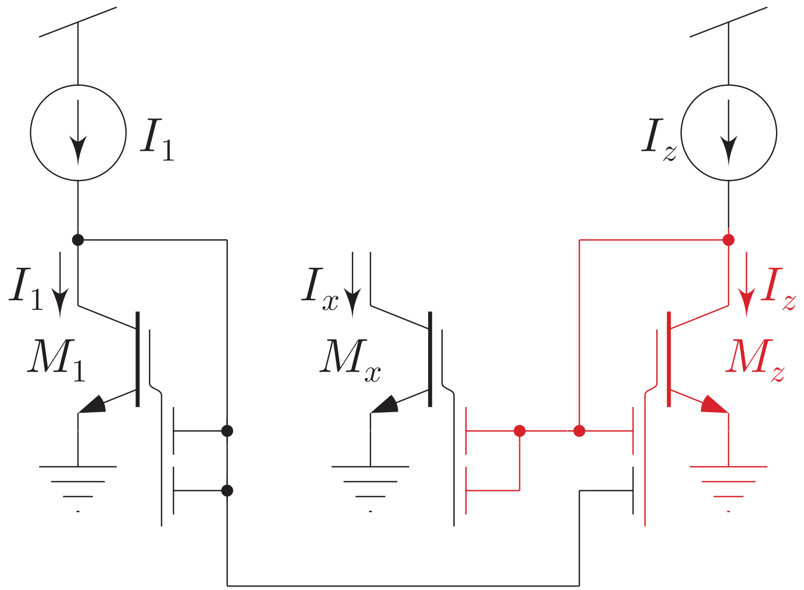

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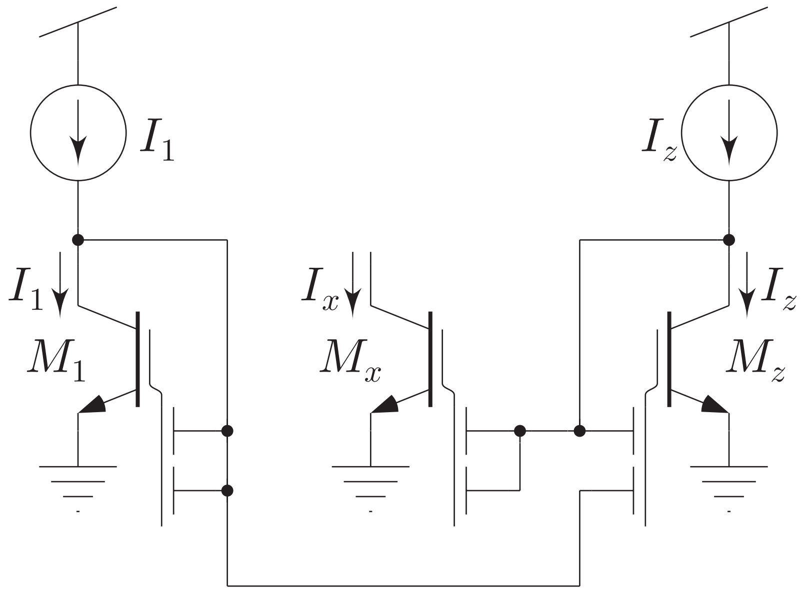

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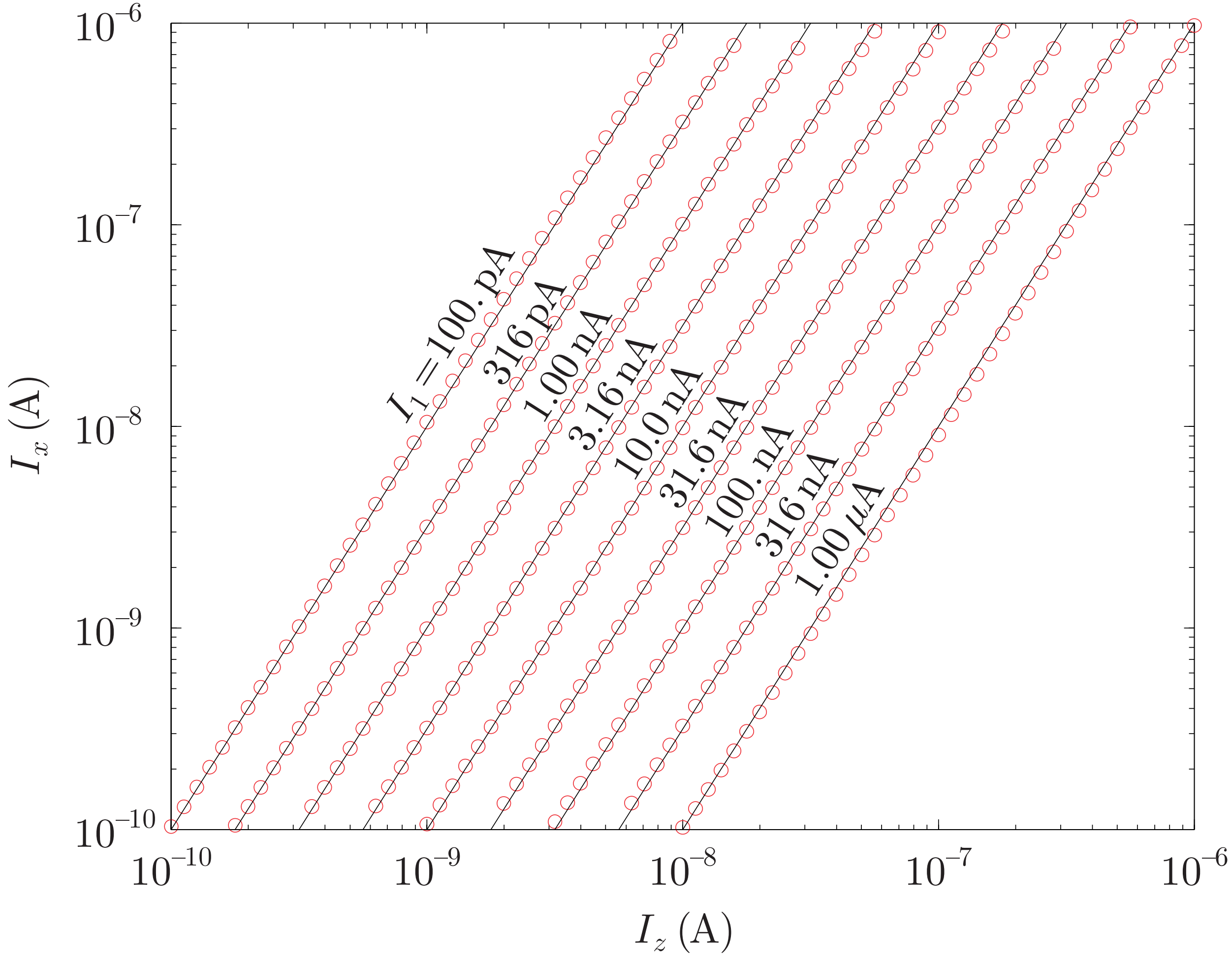

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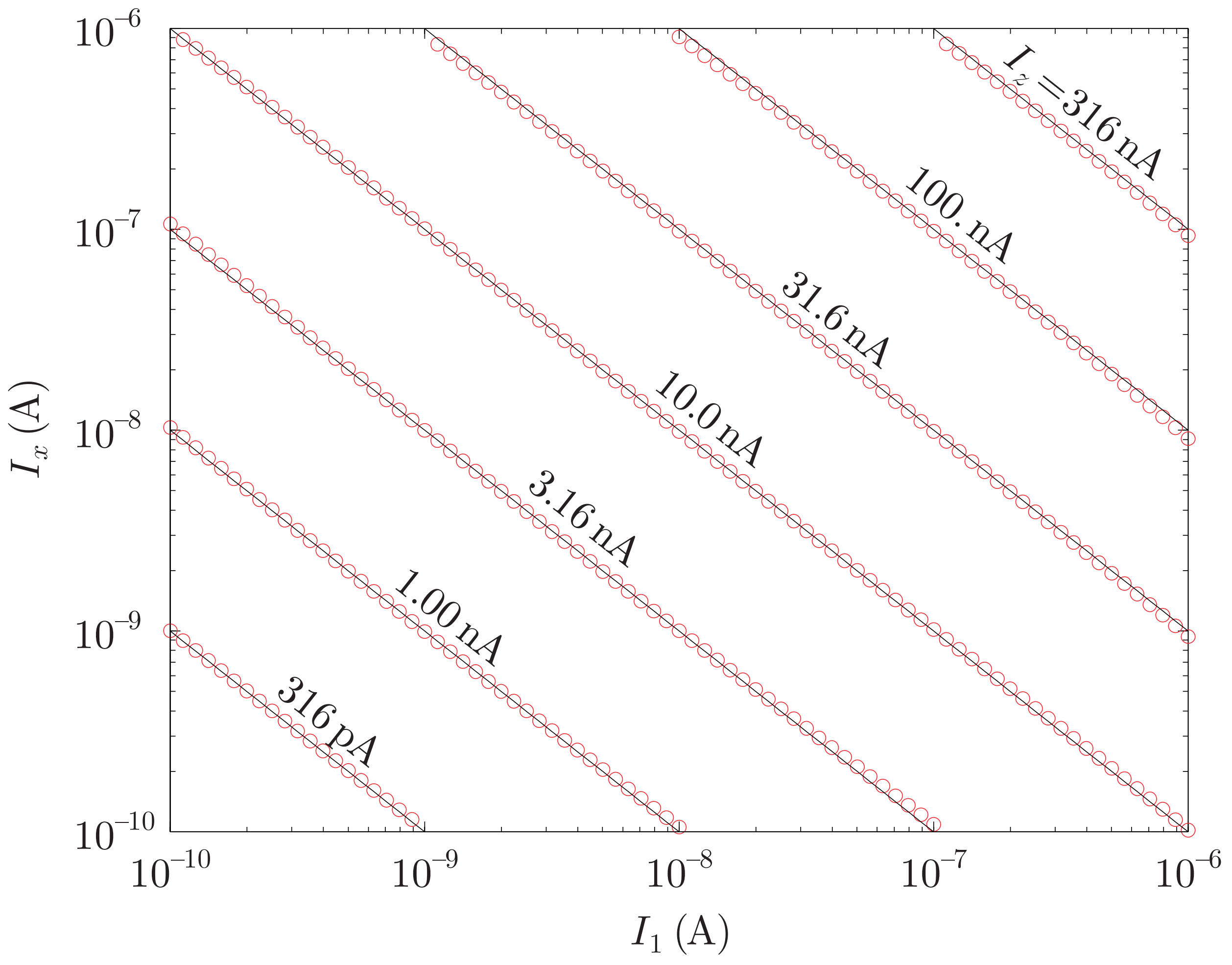

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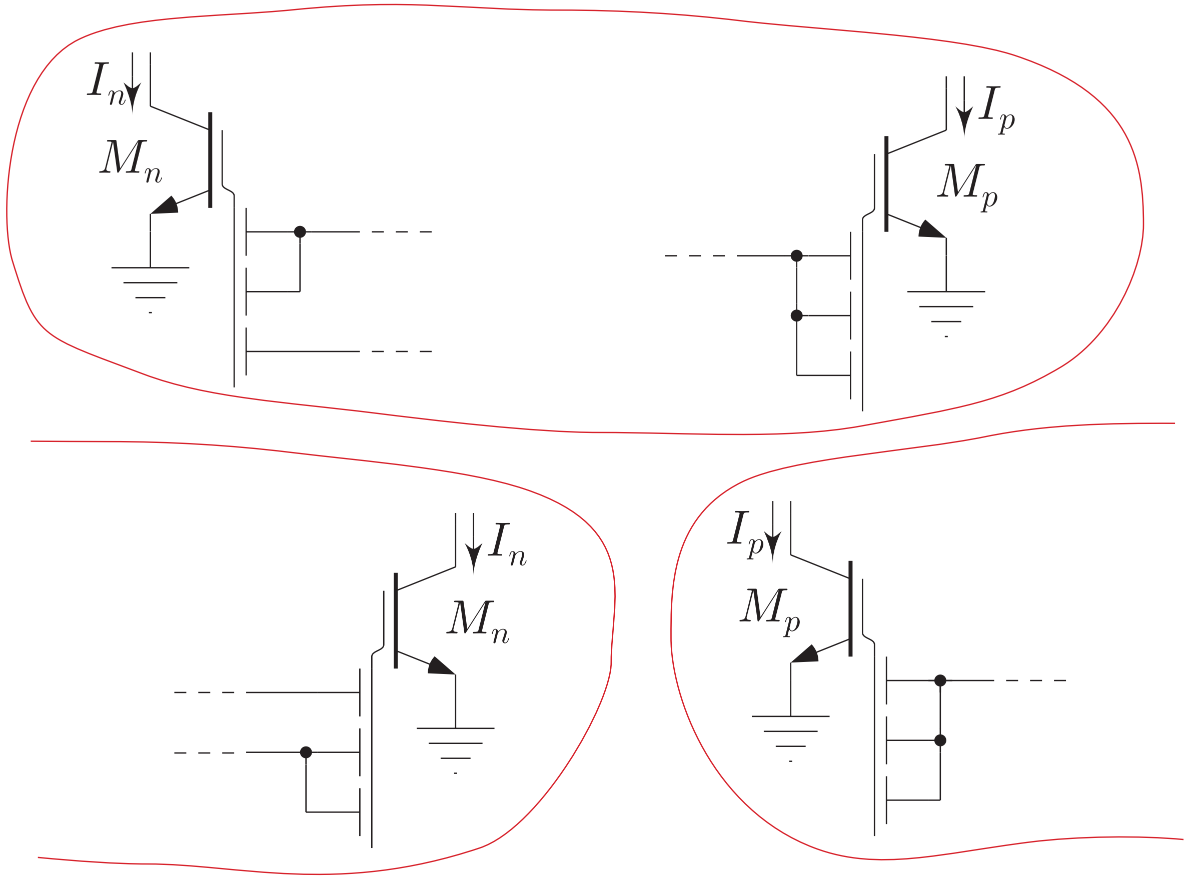

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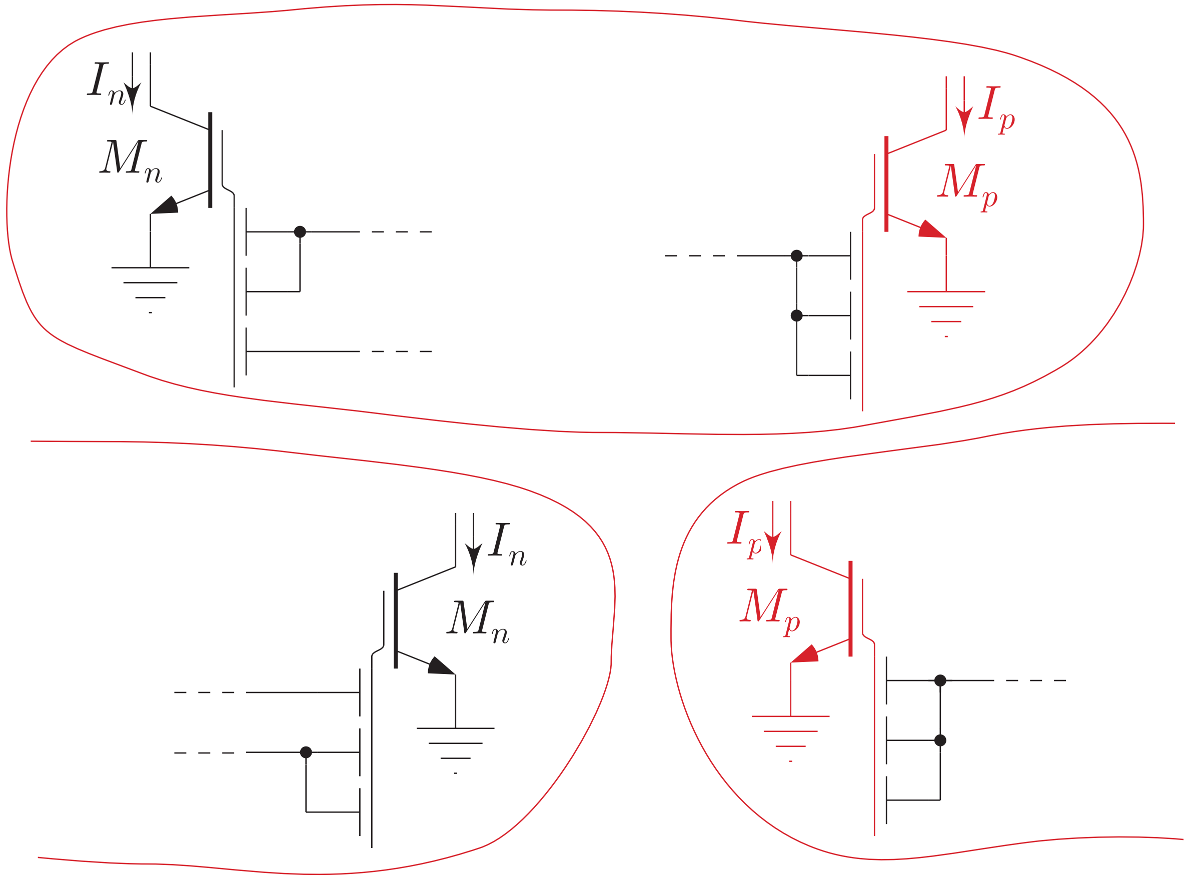

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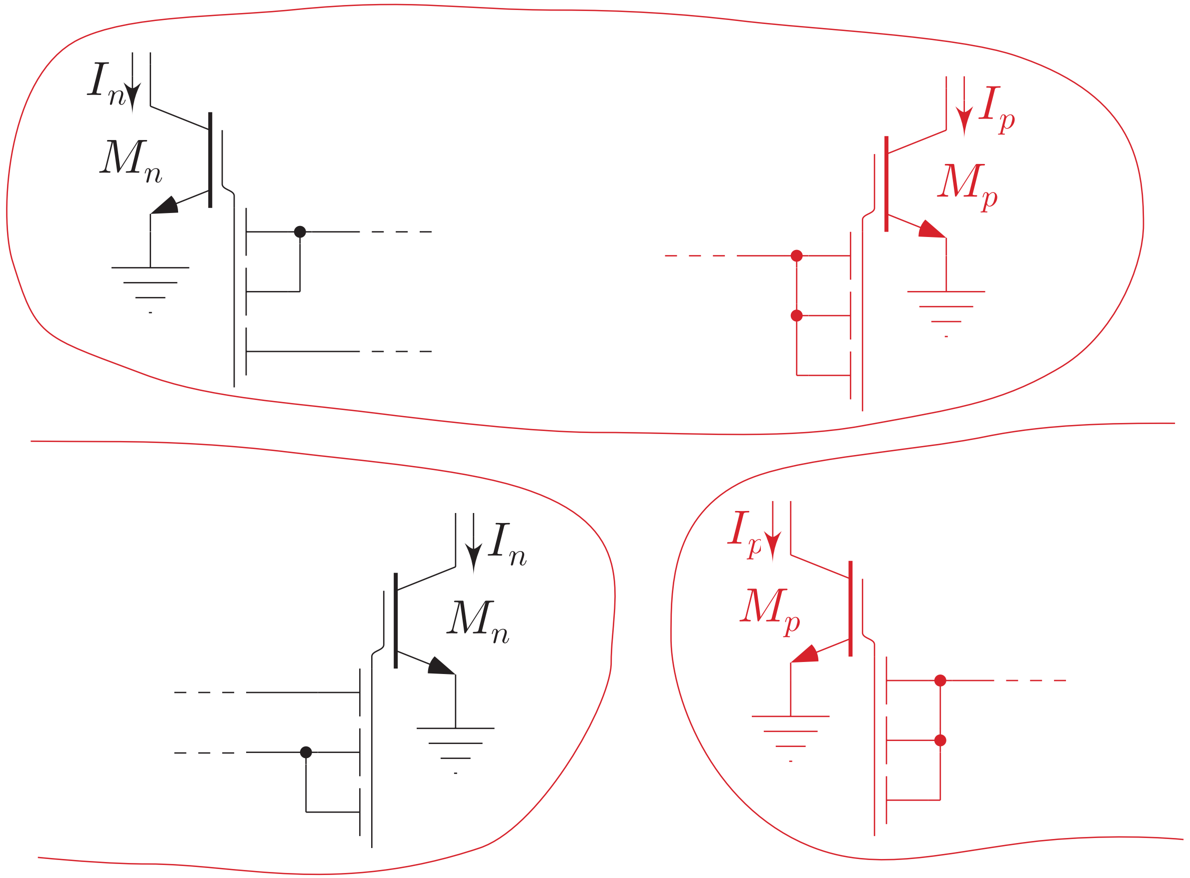

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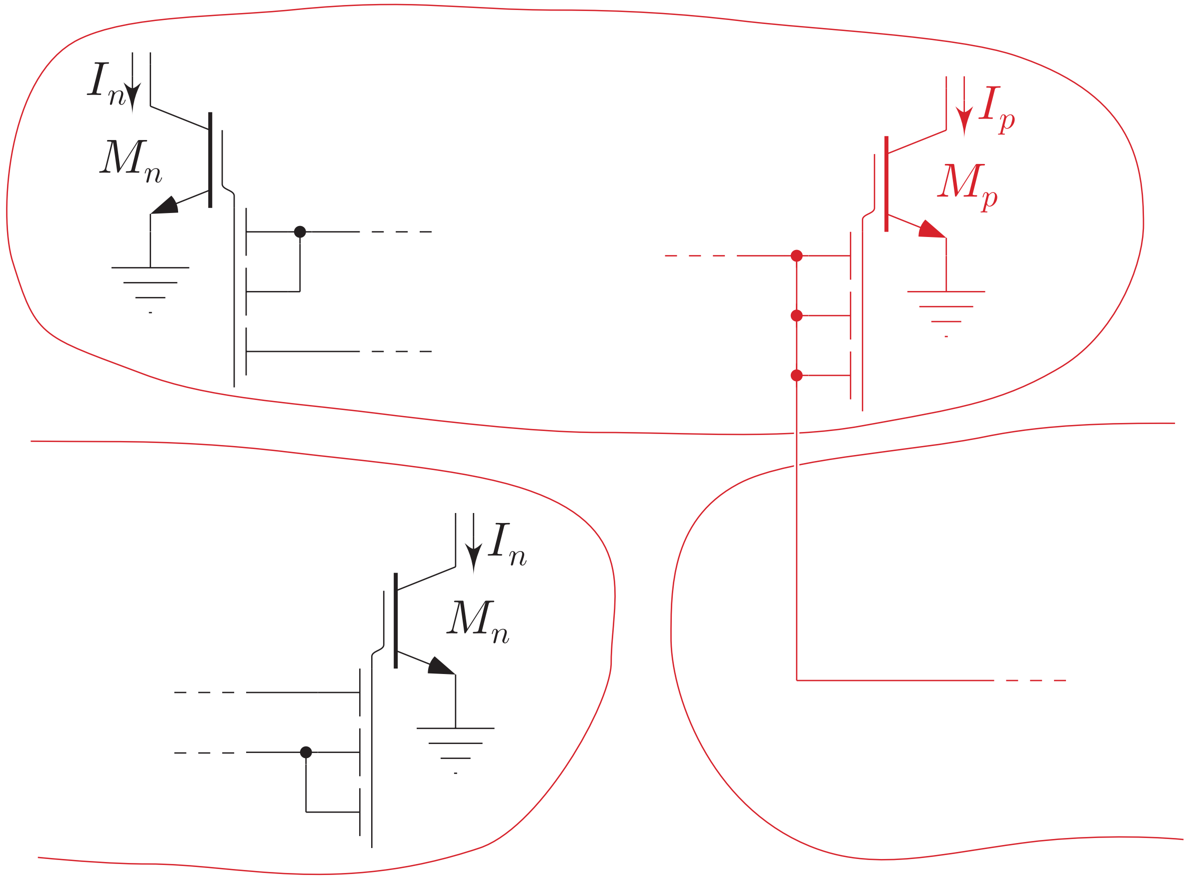

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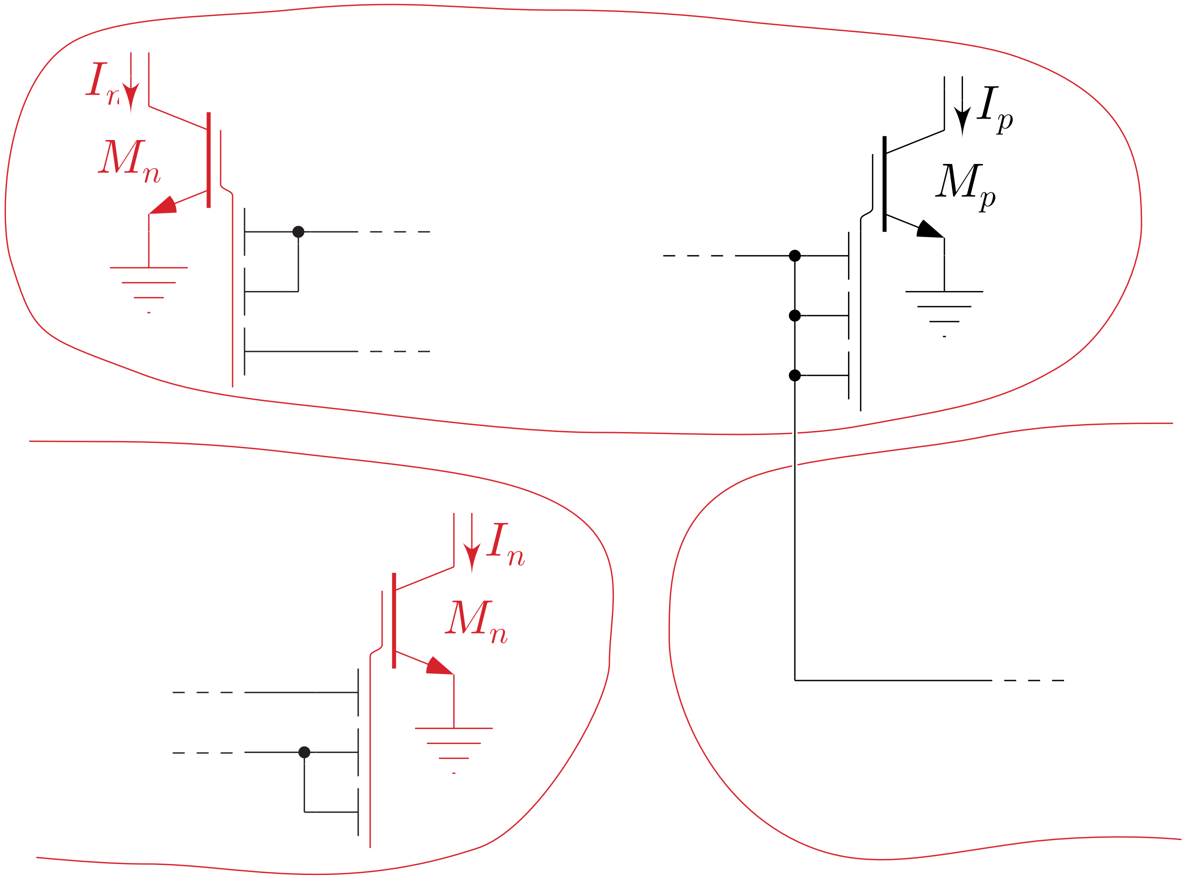

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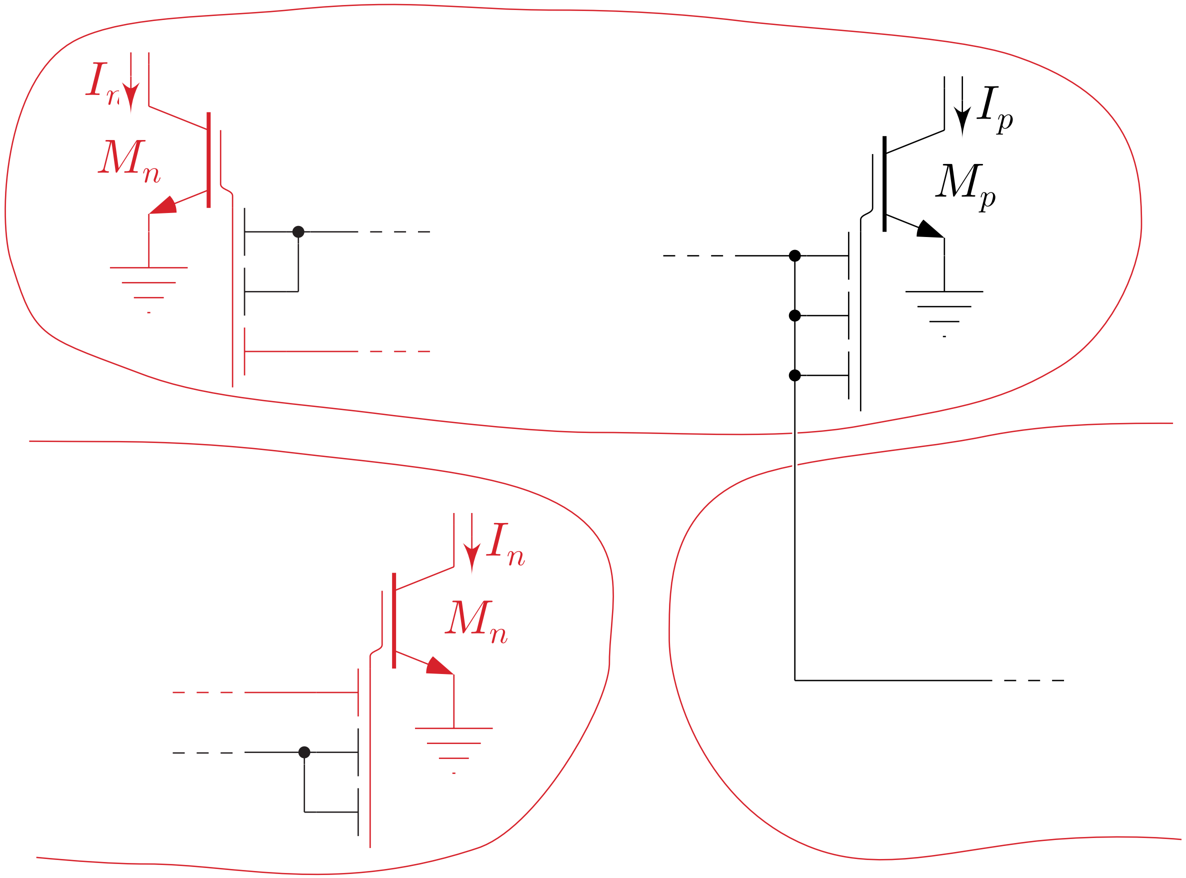

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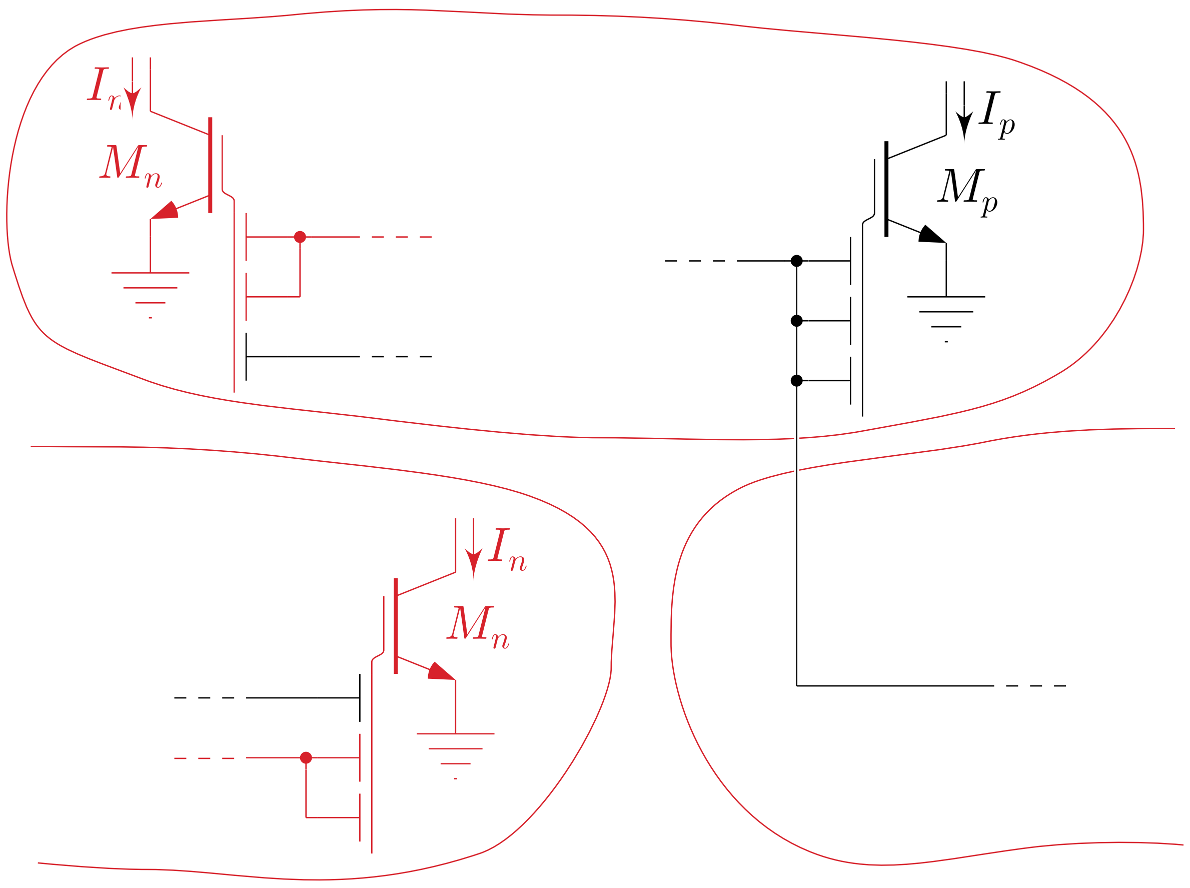

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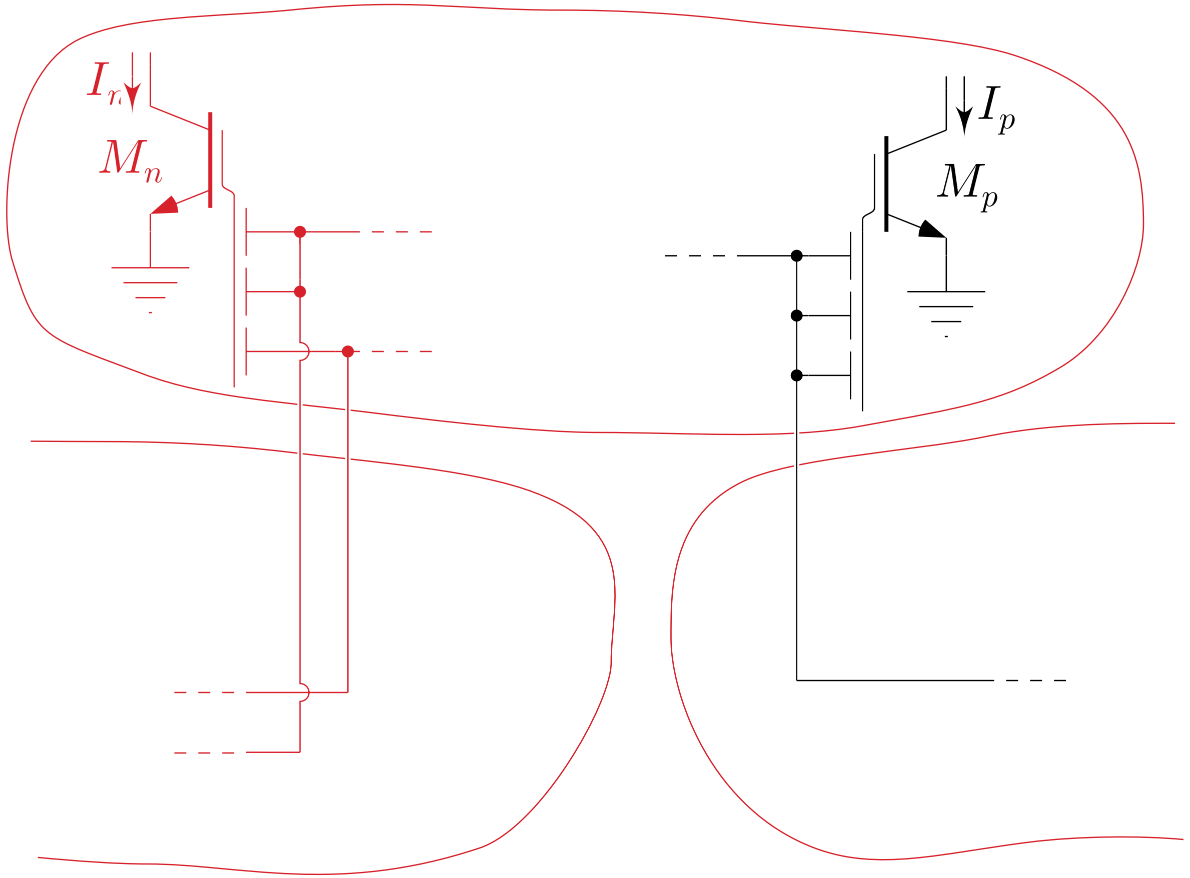

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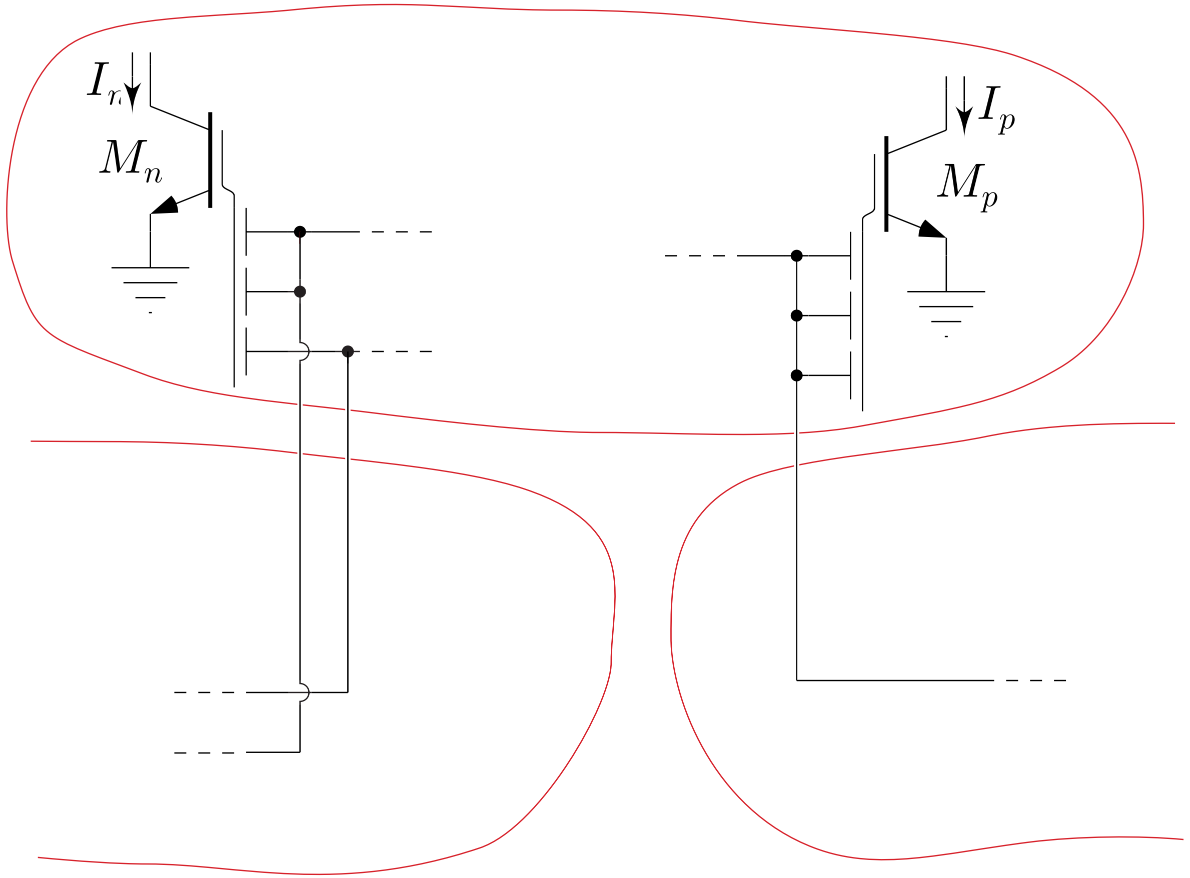

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Static MITE Network Synthesis: Vector Magnitude

Synthesize a two-dimensional vector-magnitude circuit implementing

$$r = \sqrt{x^2 + y^2}, \quad \text{where} \quad x > 0 \quad \text{and} \quad y > 0.$$

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$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \implies I_r^2 = I_x^2 + I_y^2 \implies I_r = \frac{I_x^2}{I_r} + \frac{I_y^2}{I_r}$$

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Static MITE Network Synthesis: Vector Magnitude

Synthesize a two-dimensional vector-magnitude circuit implementing

$$r = \sqrt{x^2 + y^2}, \quad \text{where} \quad x > 0 \quad \text{and} \quad y > 0.$$

We represent each signal as a ratio of a signal current to the unit current:

$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad \text{and} \quad r \equiv \frac{I_r}{I_1}.$$

We substitute these into the original equation and rearrange to obtain

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \implies I_r^2 = I_x^2 + I_y^2 \implies I_r = \underbrace{\frac{I_x^2}{I_r}}_{I_{r1}} + \underbrace{\frac{I_y^2}{I_r}}_{I_{r2}}$$

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Static MITE Network Synthesis: Vector Magnitude

TLP: $I_{r1}I_r = I_x^2$

$I_{r2}I_r = I_y^2$

KCL: $I_r = I_{r1} + I_{r2}$

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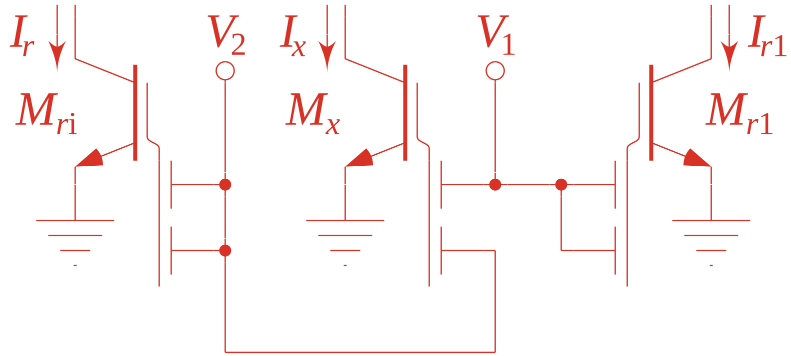

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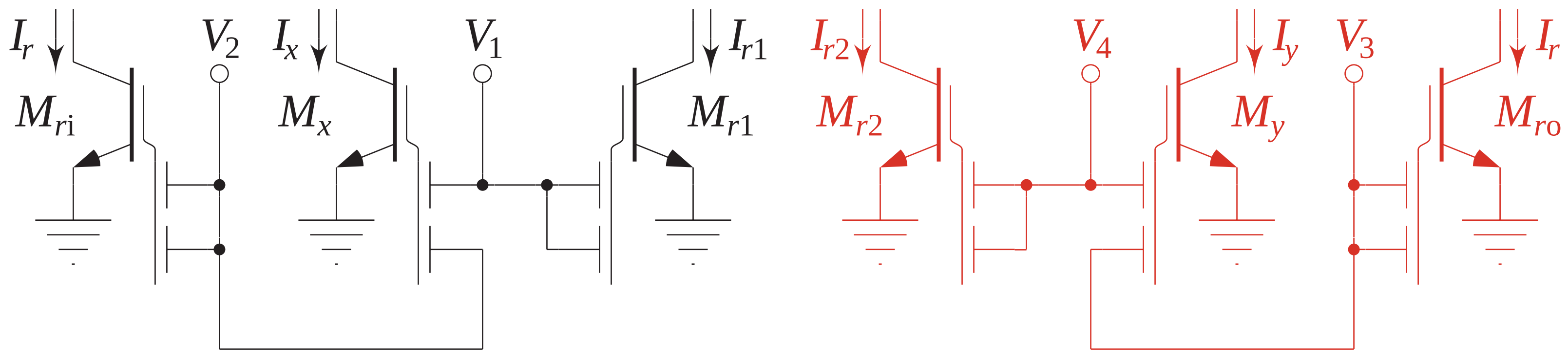

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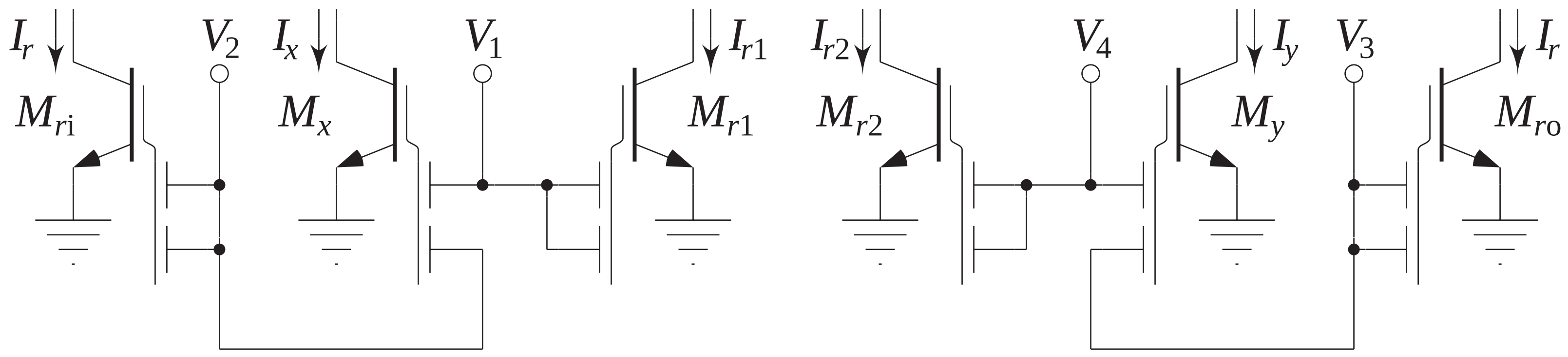

Static MITE Network Synthesis: Vector Magnitude

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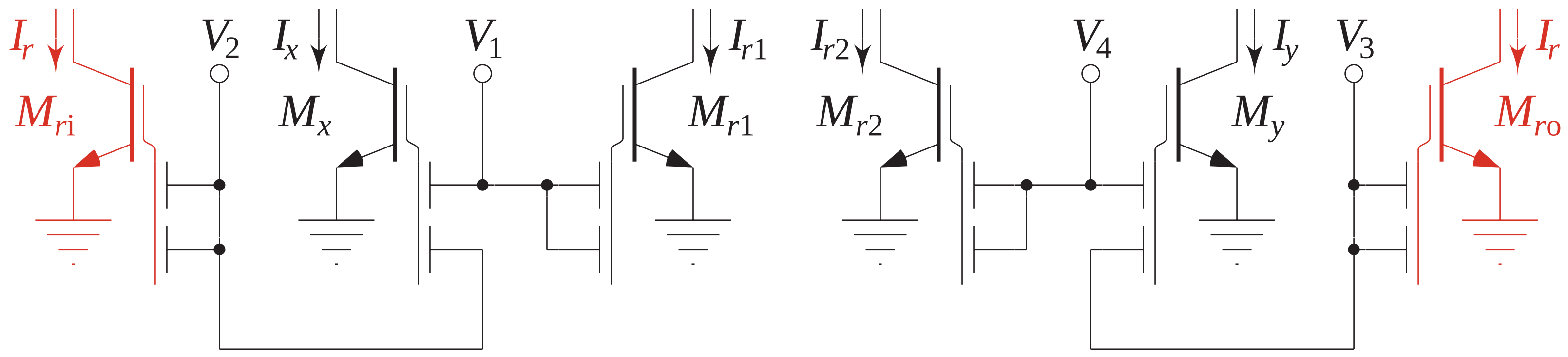

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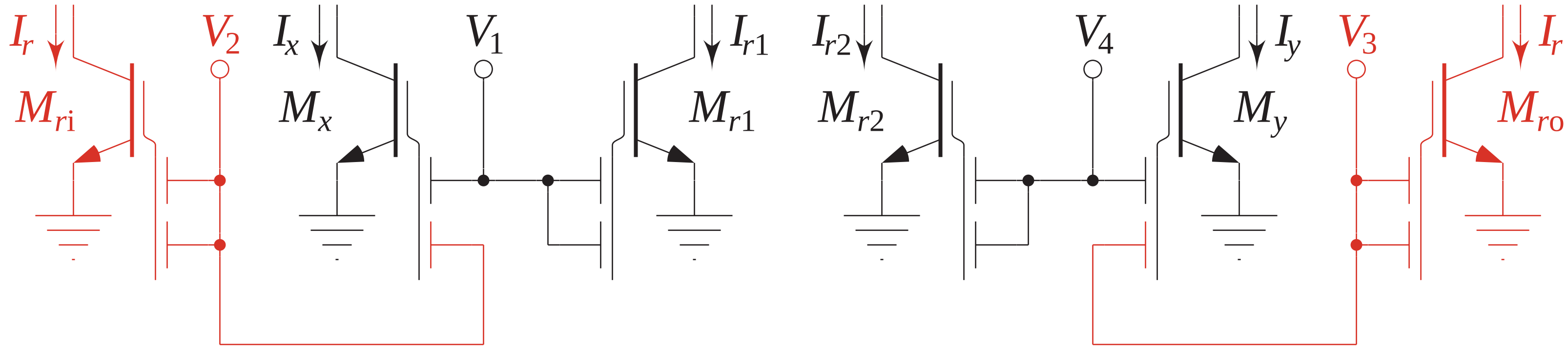

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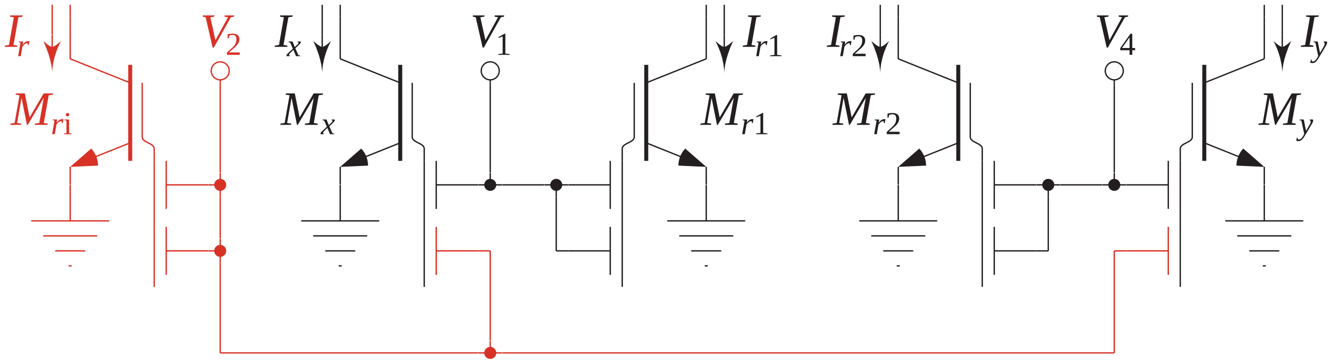

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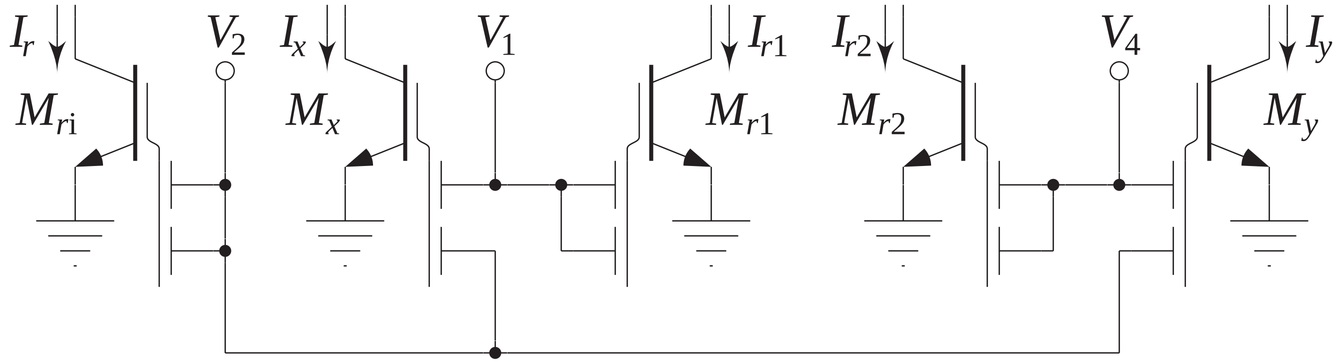

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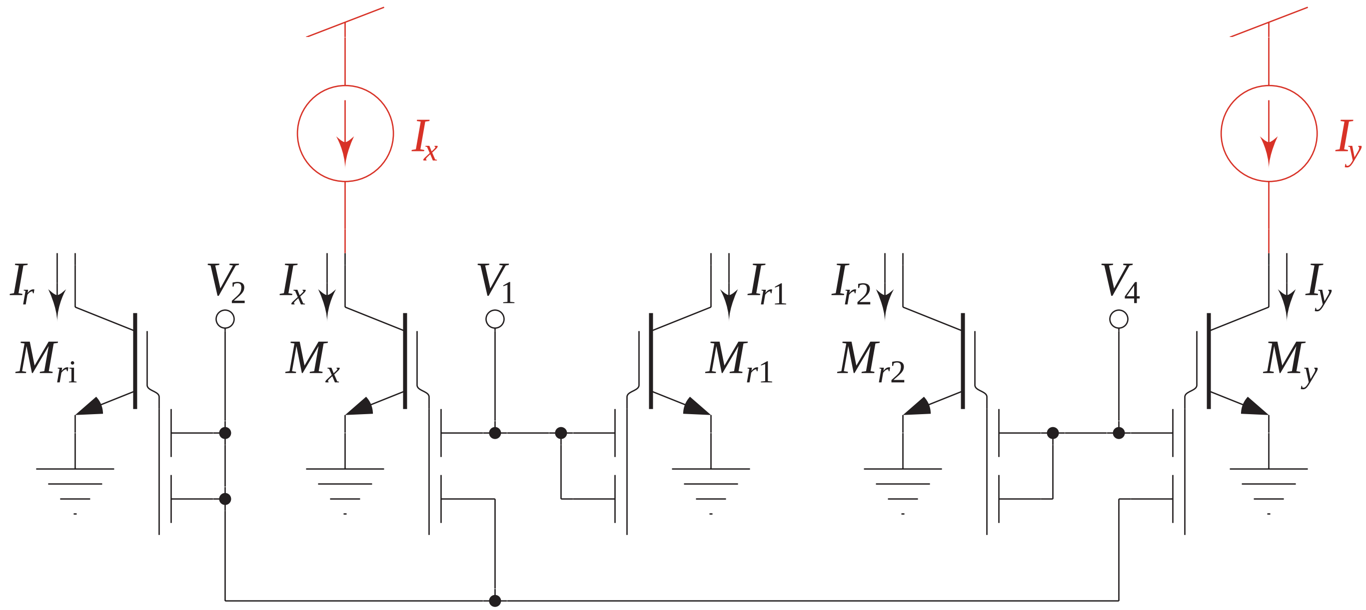

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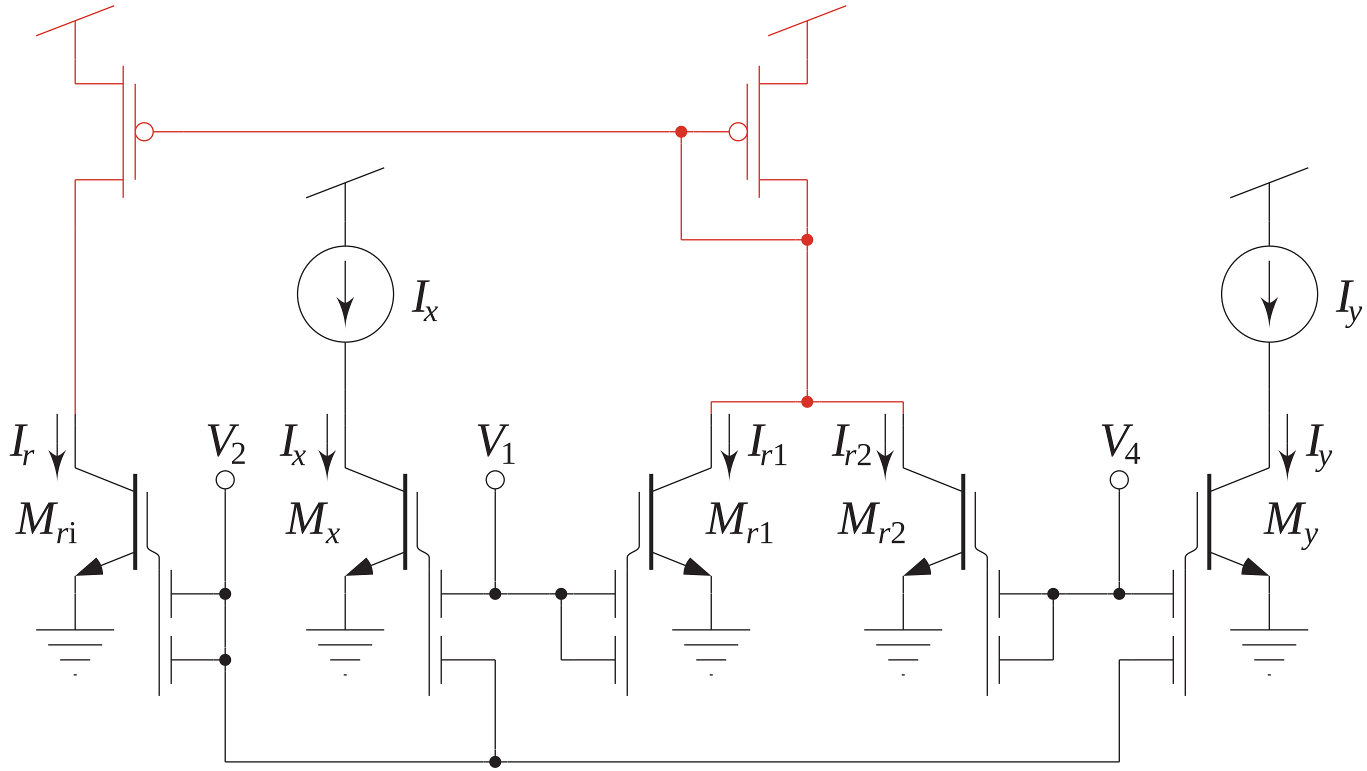

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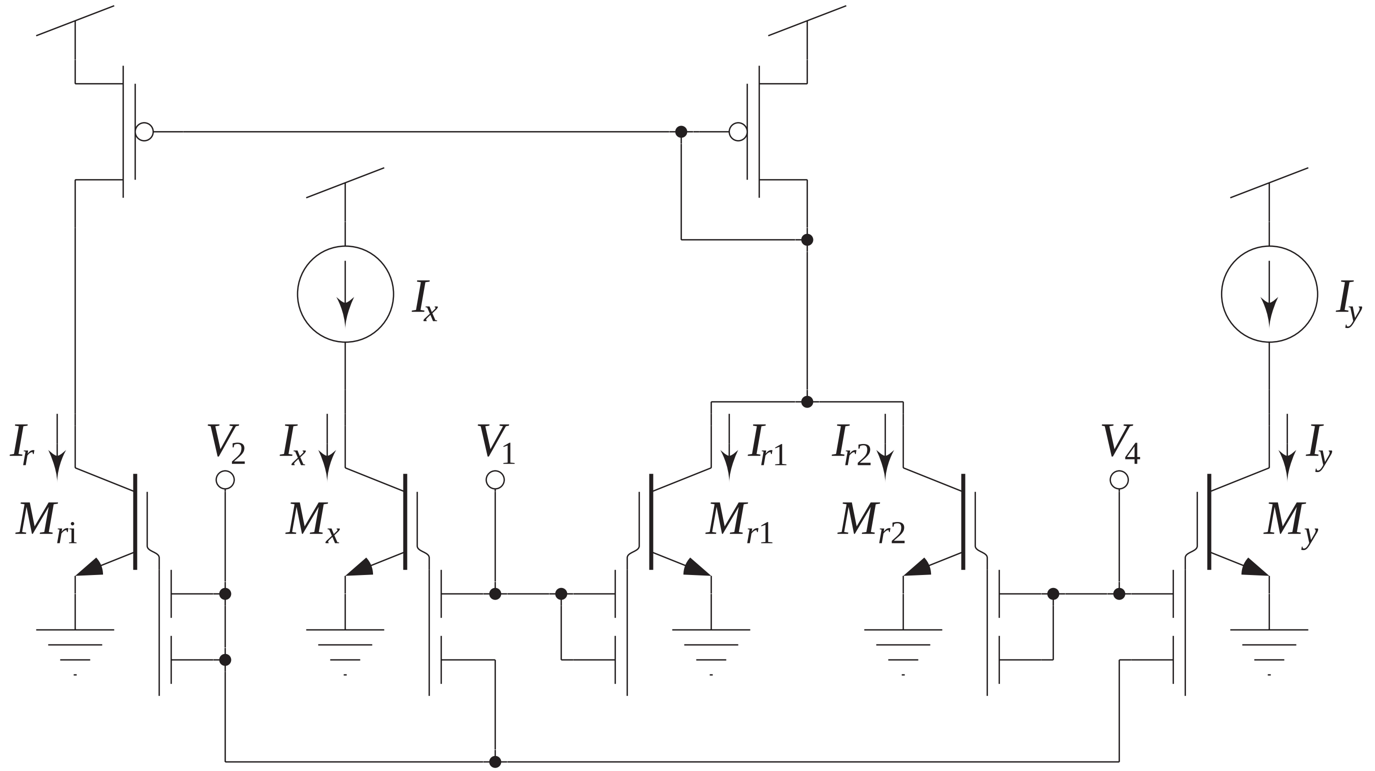

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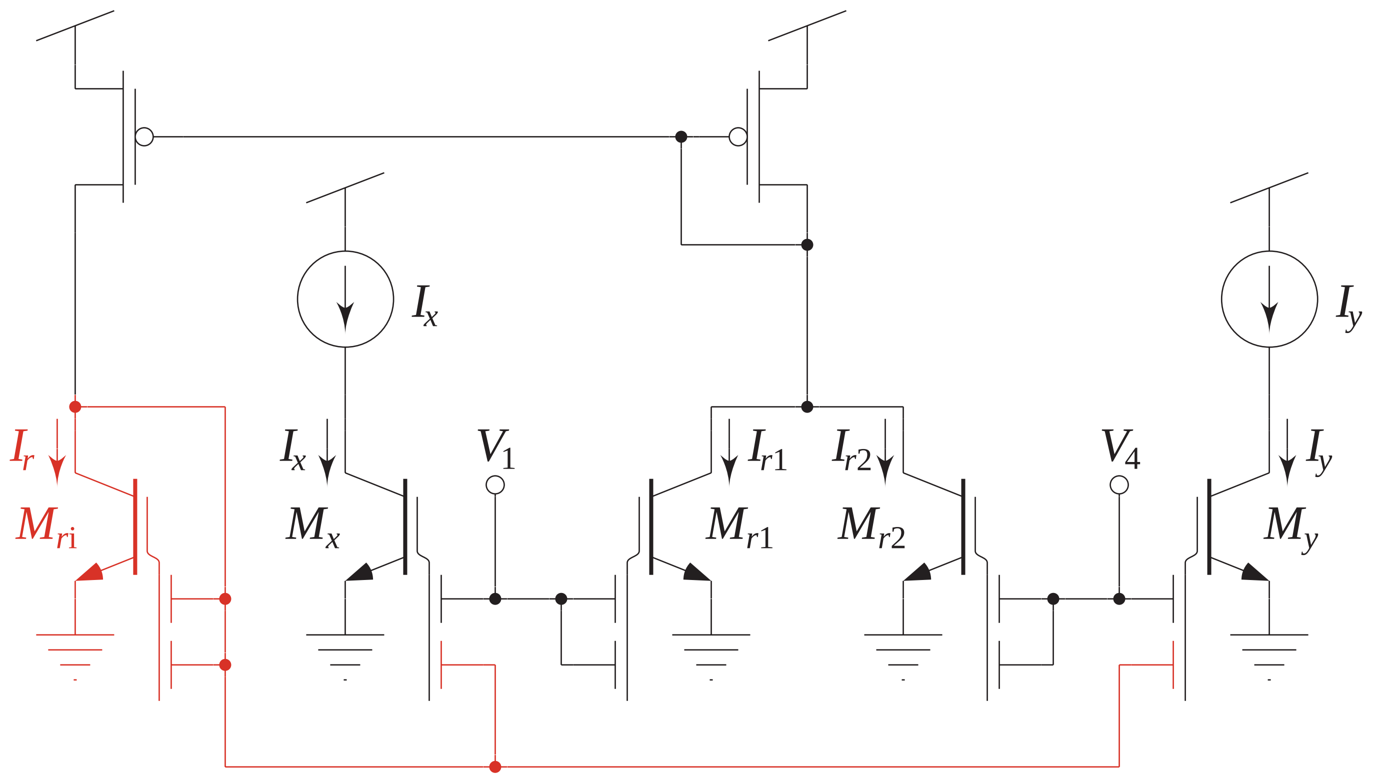

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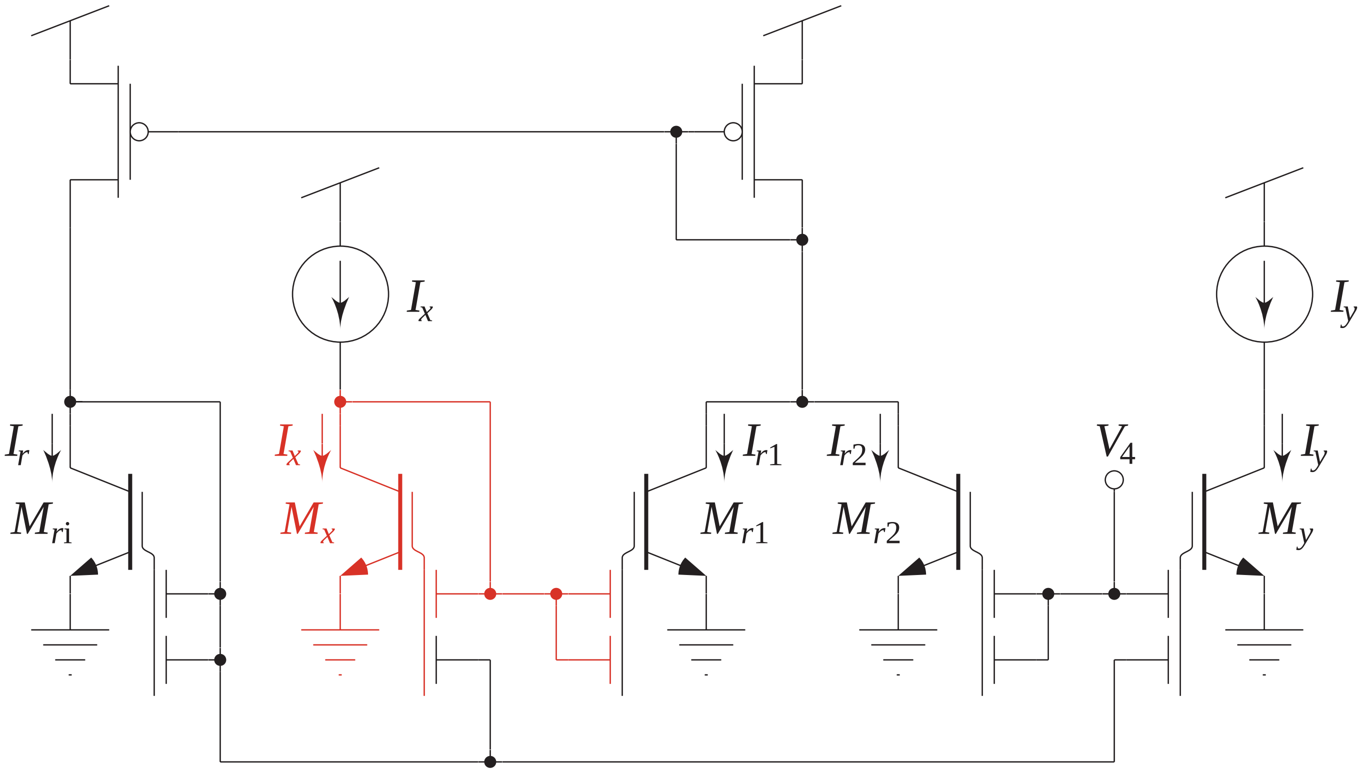

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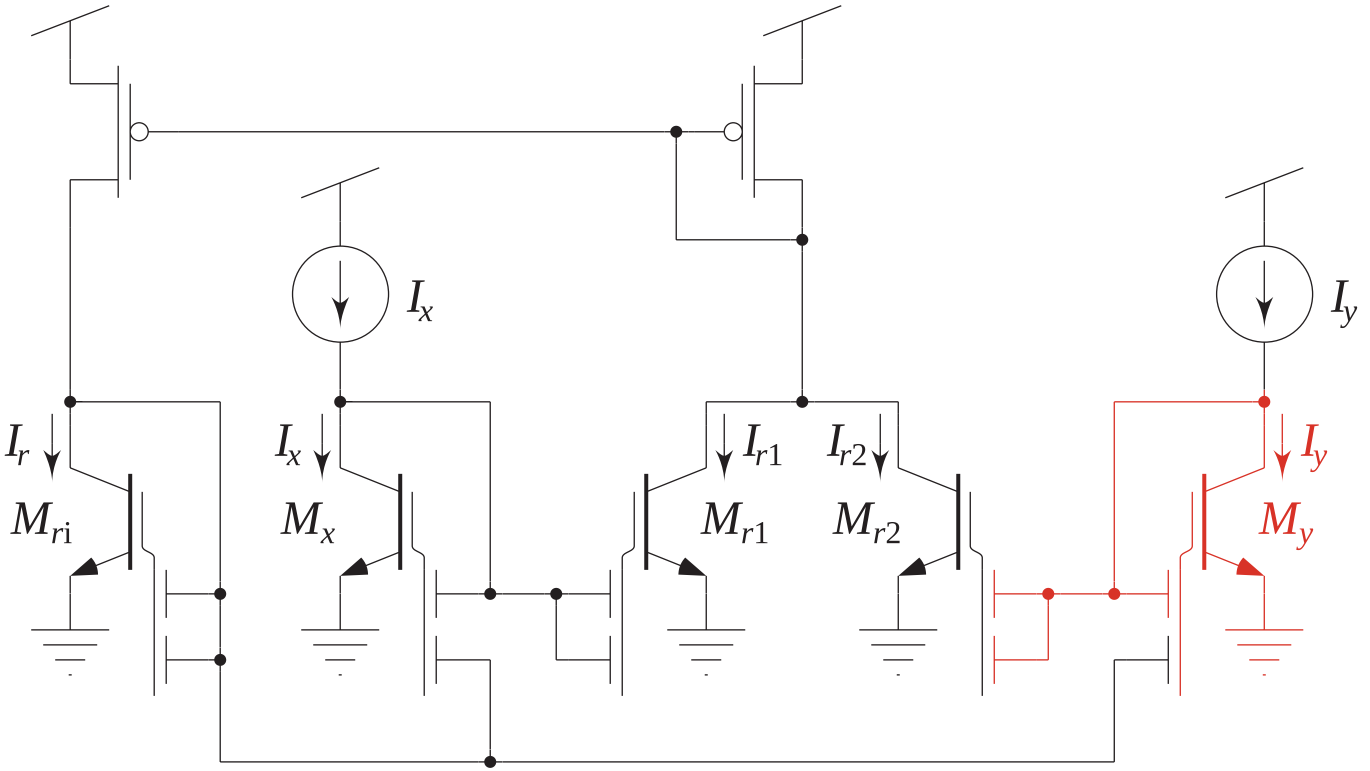

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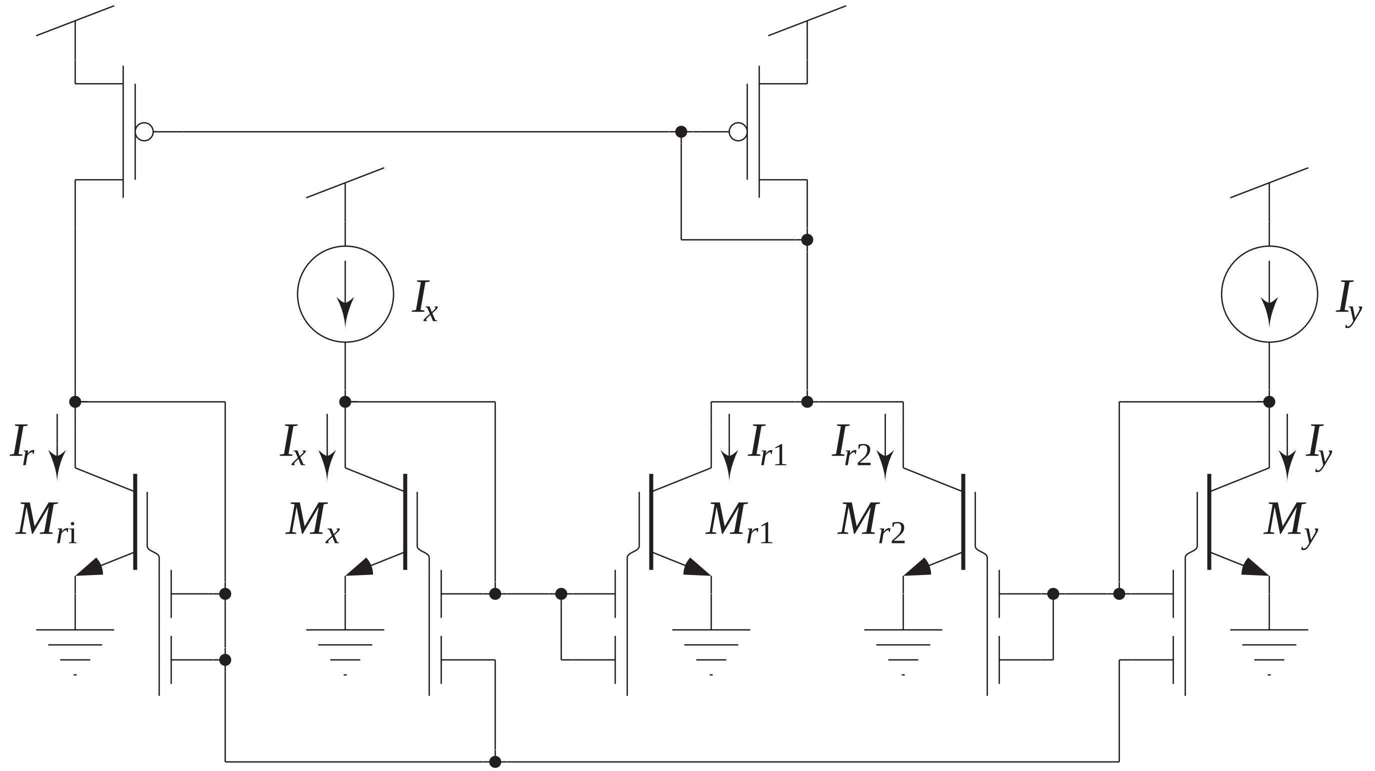

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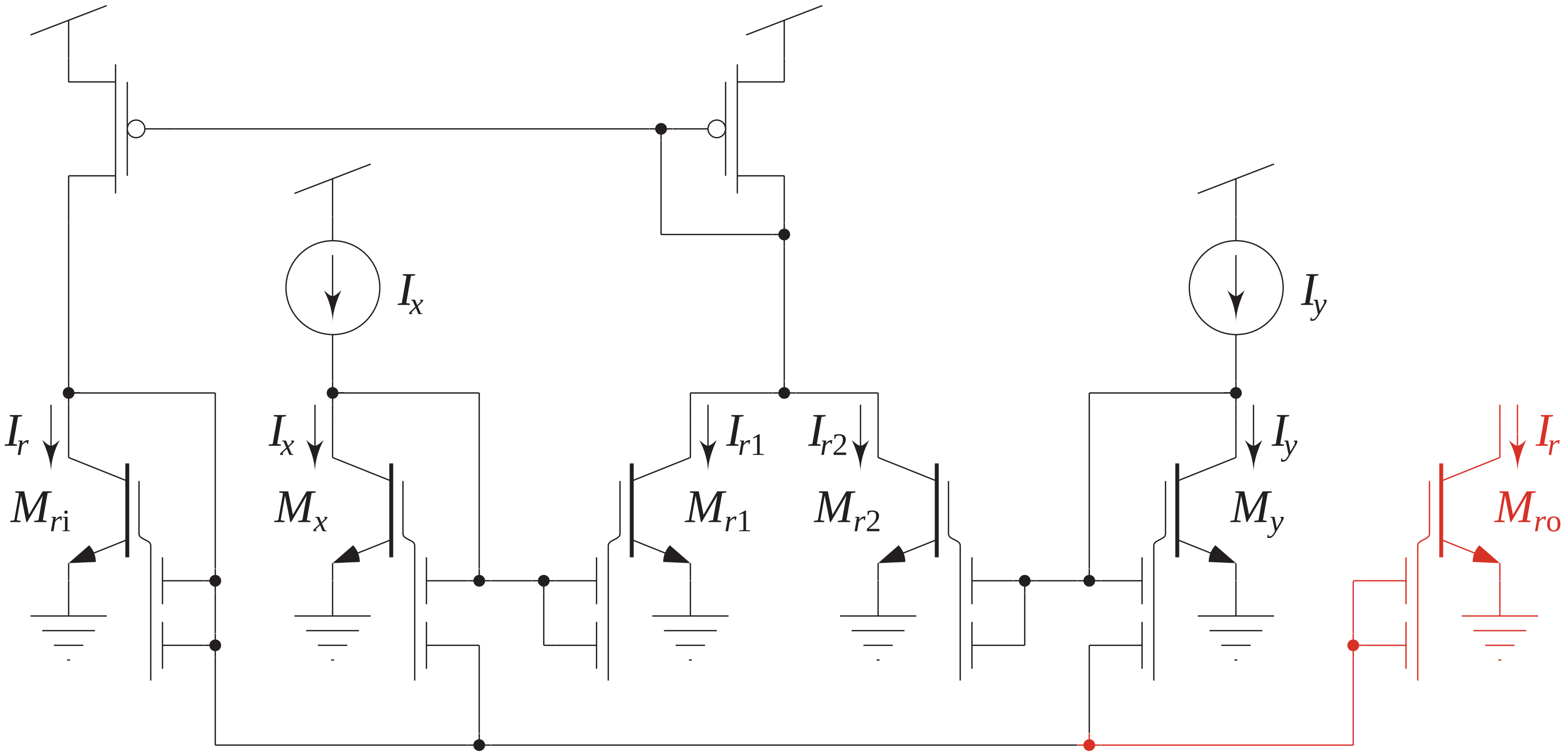

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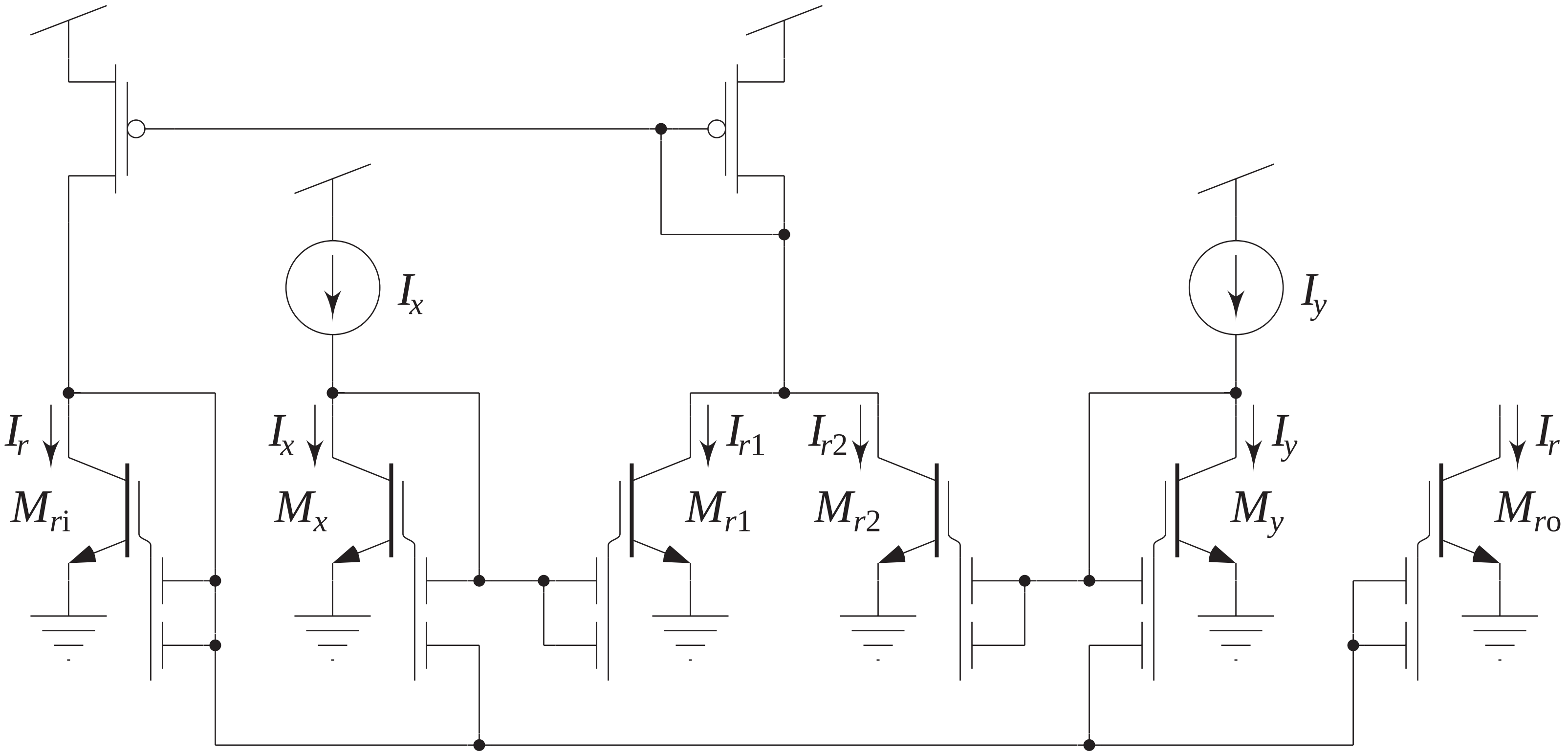
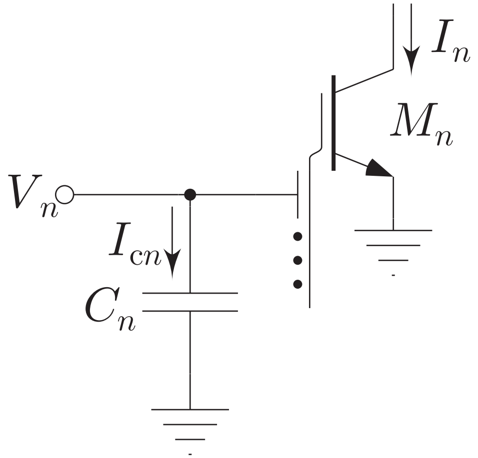
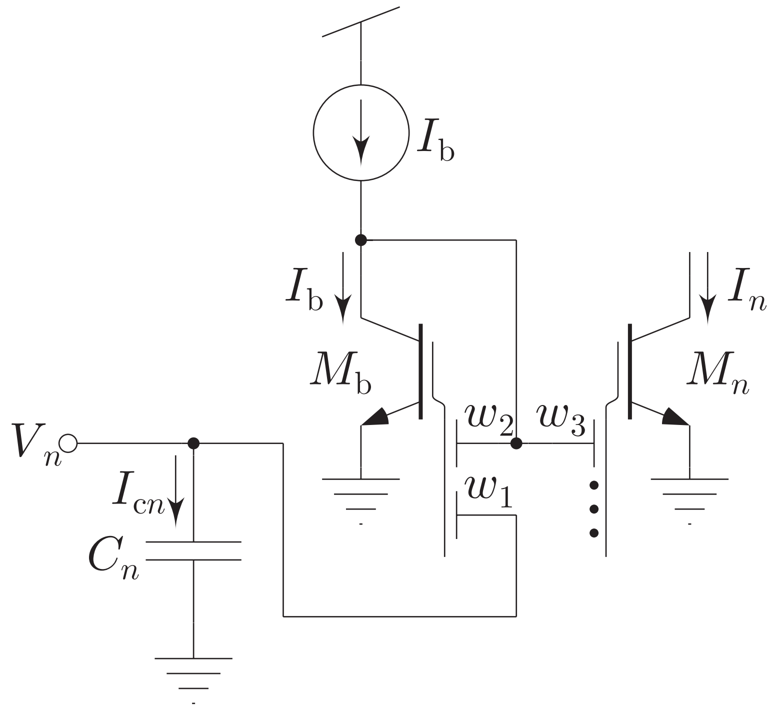


Dynamic MITE Network Synthesis: Output Structures



$$I_n \propto e^{wV_n/U_\mathrm{T}}$$

$$\frac{\partial I_n}{\partial V_n} = \frac{w}{U_\mathrm{T}} I_n$$



$$I_n \propto e^{-wV_n/U_\mathrm{T}}$$

$$\frac{\partial I_n}{\partial V_n} = -\frac{w}{U_\mathrm{T}} I_n$$

Dynamic MITE Network Synthesis: First-Order LPF

Synthesize a first-order low-pass filter described by

$$\tau \frac{dy}{dt} + y = x, \quad \text{where} \quad x > 0.$$

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Substituting these into the ODE, we obtain

$$\tau \frac{d}{dt}\left(\frac{I_y}{I_1}\right) + \frac{I_y}{I_1} = \frac{I_x}{I_1}$$

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Substituting these into the ODE, we obtain

$$\tau \frac{d}{dt}\left(\frac{I_y}{I_1}\right) + \frac{I_y}{I_1} = \frac{I_x}{I_1} \quad \Longrightarrow \quad \tau \frac{dI_y}{dt} + I_y = I_x.$$

Dynamic MITE Network Synthesis: First-Order LPF

To implement the time derivative, we introduce a log-compressed voltage state variable, V_y. Using the chain rule, we can express the preceding equation as

$$\tau \frac{\partial I_y}{\partial V_y} \cdot \frac{dV_y}{dt} + I_y = I_x$$

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Dynamic MITE Network Synthesis: First-Order LPF

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$$\tau \frac{\partial I_y}{\partial V_y} \cdot \frac{dV_y}{dt} + I_y = I_x \quad \Longrightarrow \quad \tau \left(-\frac{w}{U_\mathrm{T}} I_y \right) \frac{dV_y}{dt} + I_y = I_x$$

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$$\Longrightarrow \quad -\frac{I_c}{I_\tau} + 1 = \frac{I_x}{I_y}$$

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Dynamic MITE Network Synthesis: First-Order LPF

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$$\tau\frac{\partial I_y}{\partial V_y}\cdot\frac{dV_y}{dt}+I_y=I_x \quad\Longrightarrow\quad \tau\left(-\frac{w}{U_\mathrm{T}}I_y\right)\frac{dV_y}{dt}+I_y=I_x$$

$$\Longrightarrow\ -\frac{w\tau}{U_\mathrm{T}}\cdot\frac{dV_y}{dt}+1=\frac{I_x}{I_y} \quad\Longrightarrow\quad -\underbrace{\frac{w\tau}{CU_\mathrm{T}}}_{1/I_\tau}\cdot\underbrace{C\frac{dV_y}{dt}}_{I_c}+1=\frac{I_x}{I_y}$$

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Dynamic MITE Network Synthesis: First-Order LPF

TLP: $I_p I_y = I_x I_\tau$ KCL: $I_p + I_c = I_\tau$

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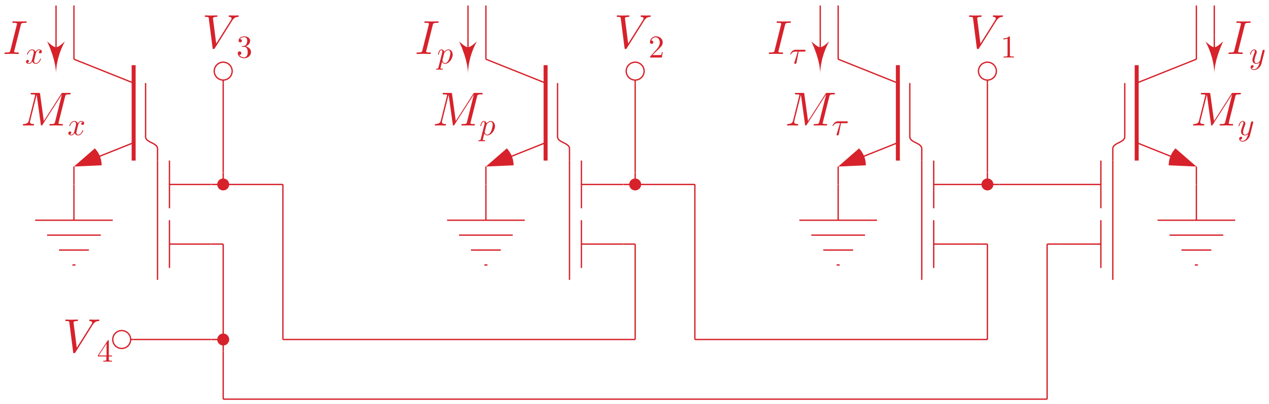

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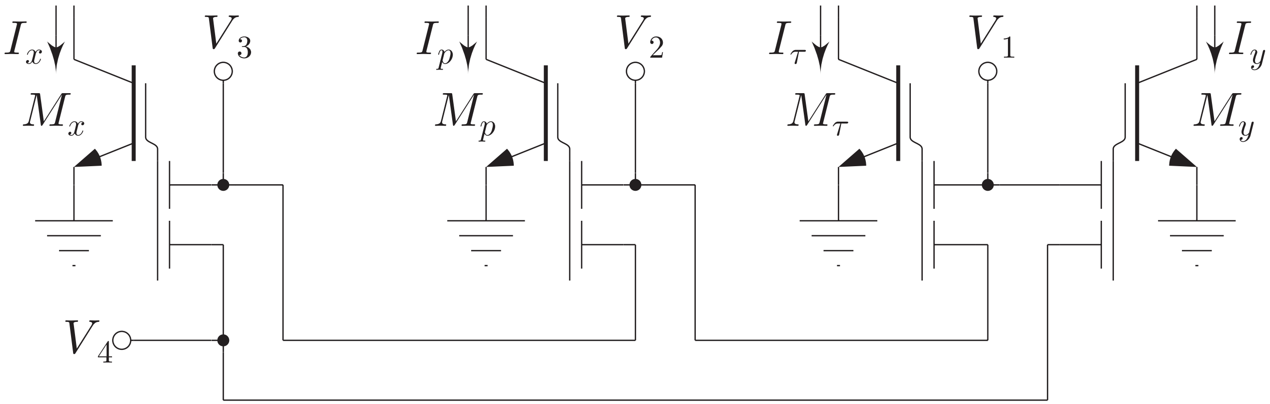

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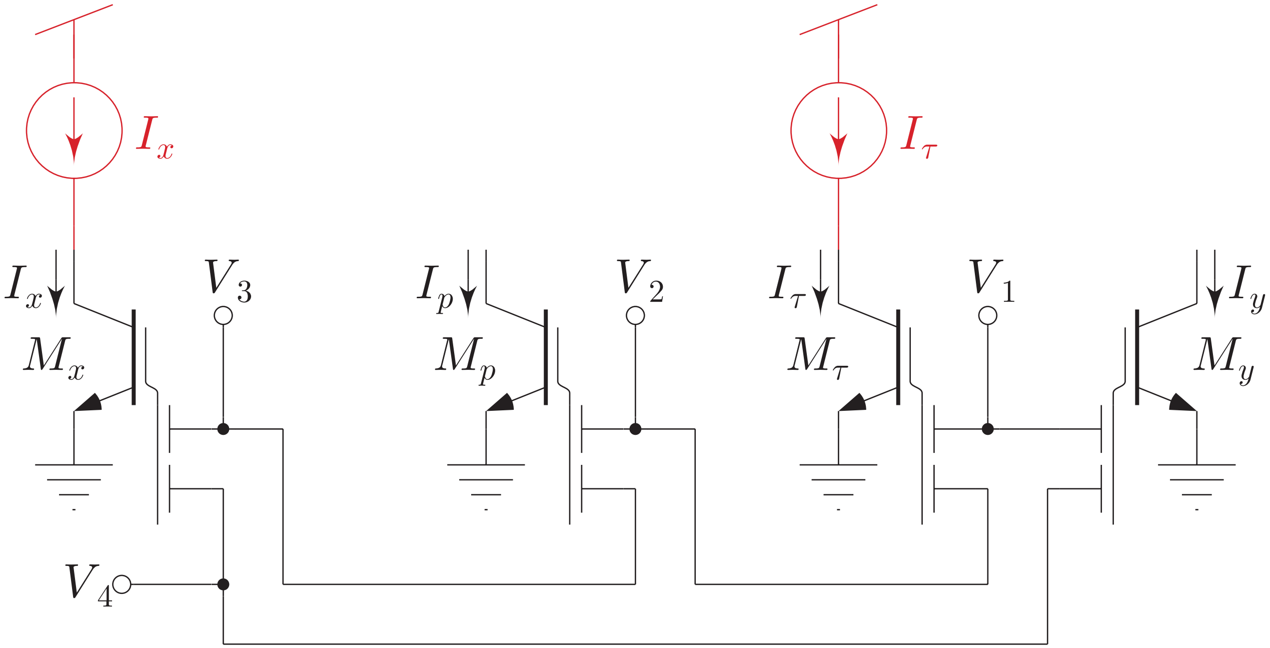

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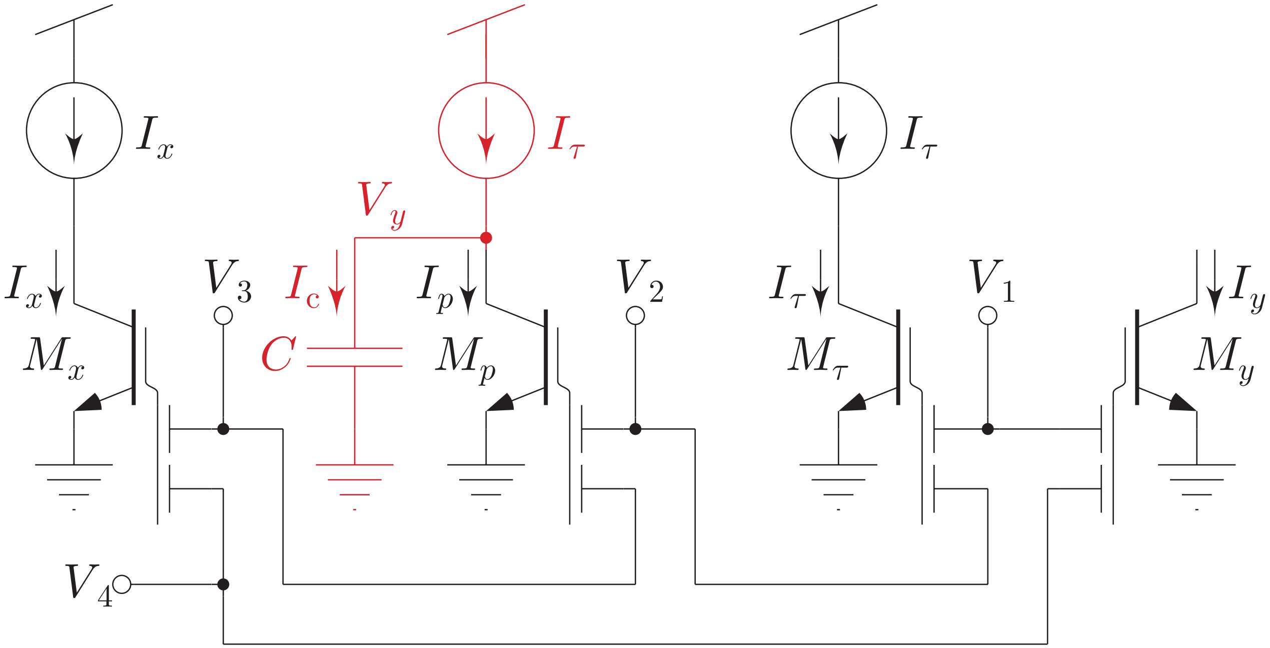

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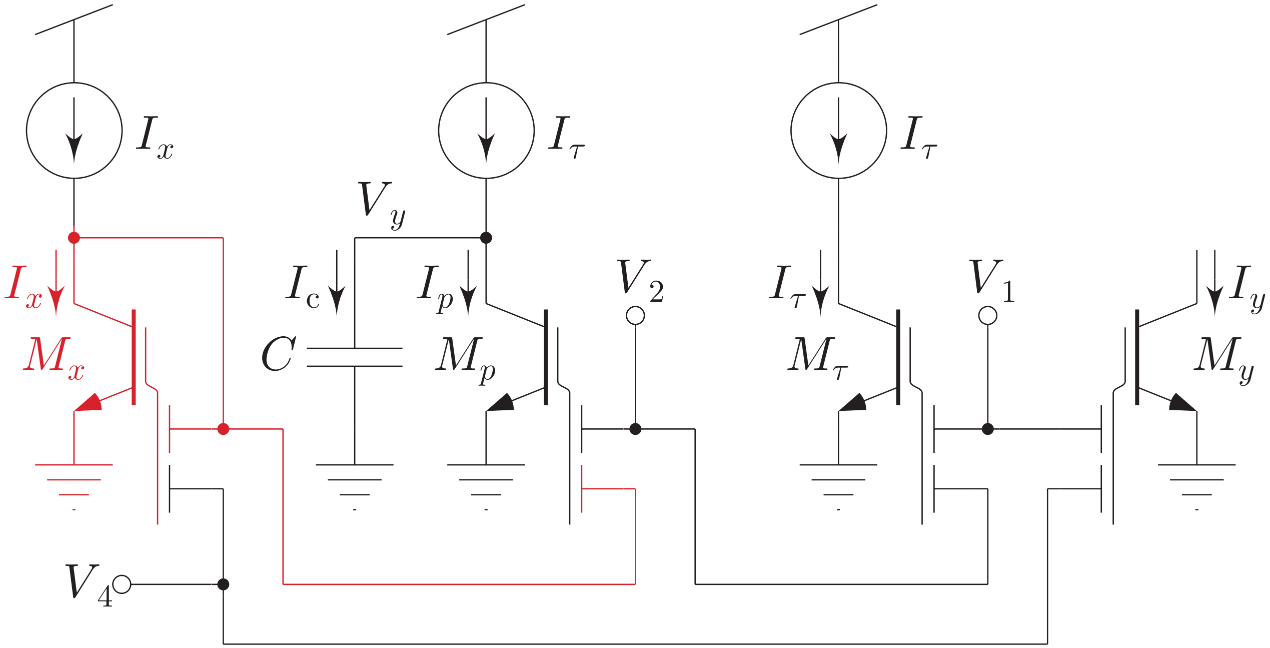

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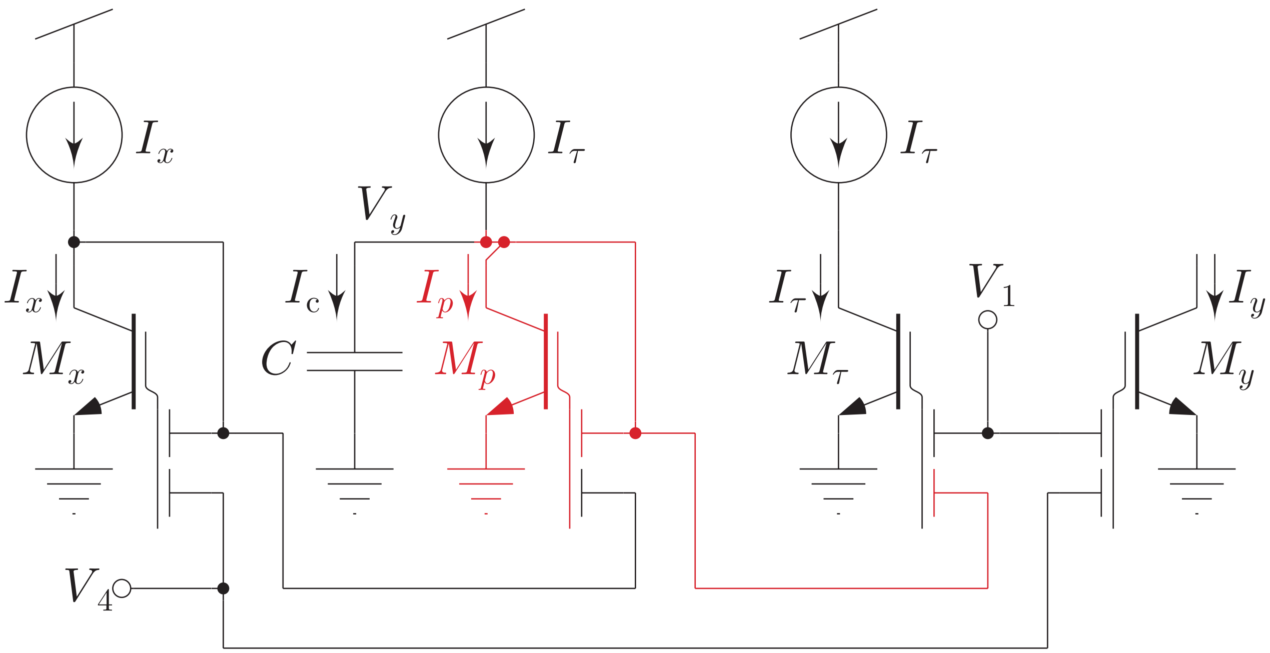

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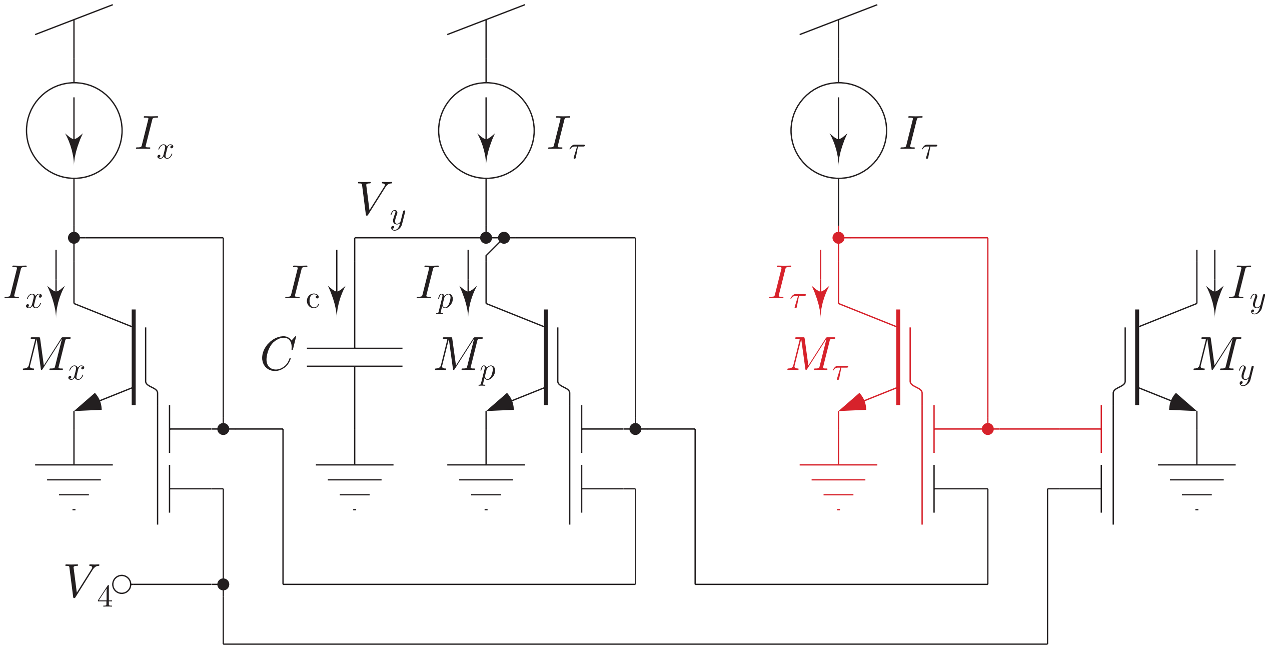

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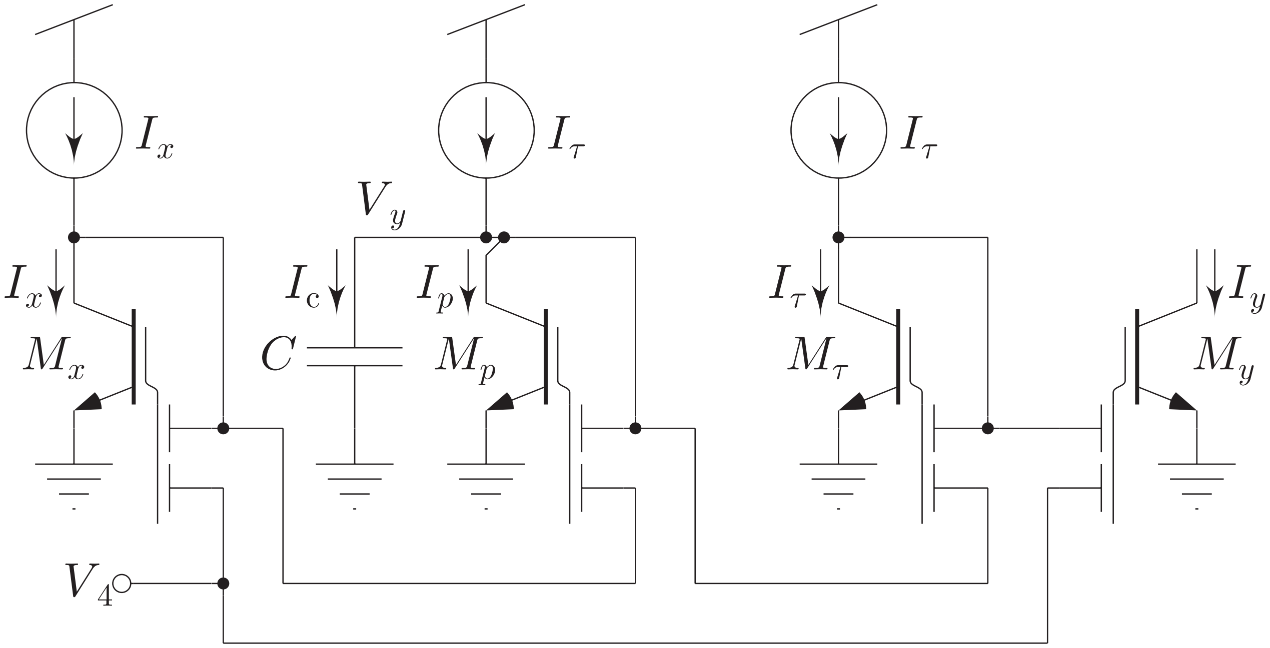

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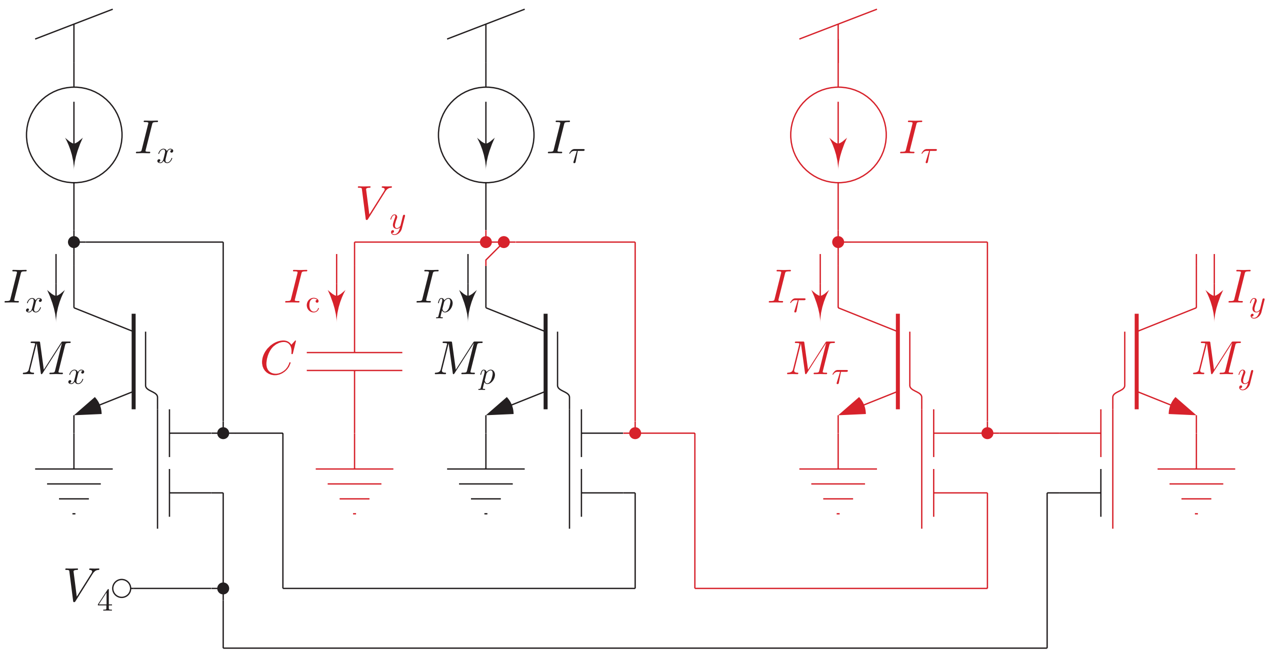

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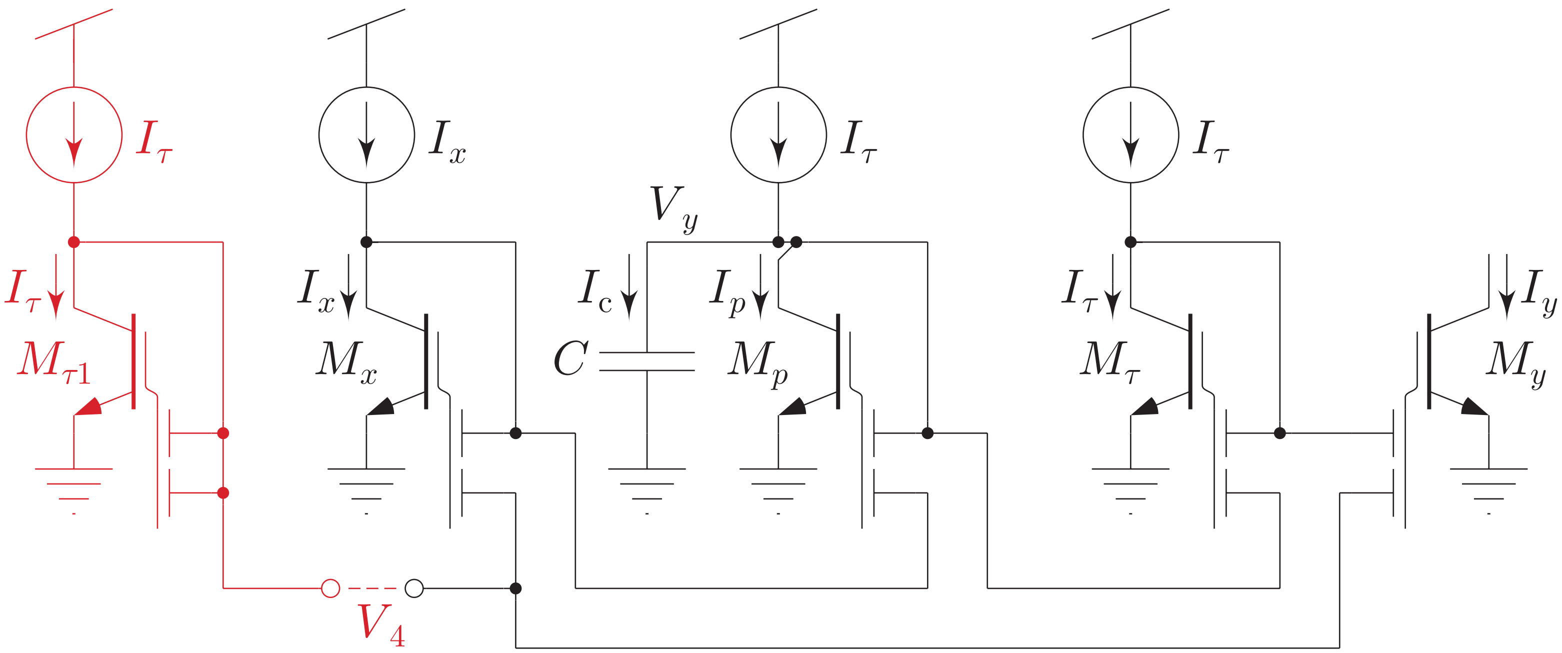

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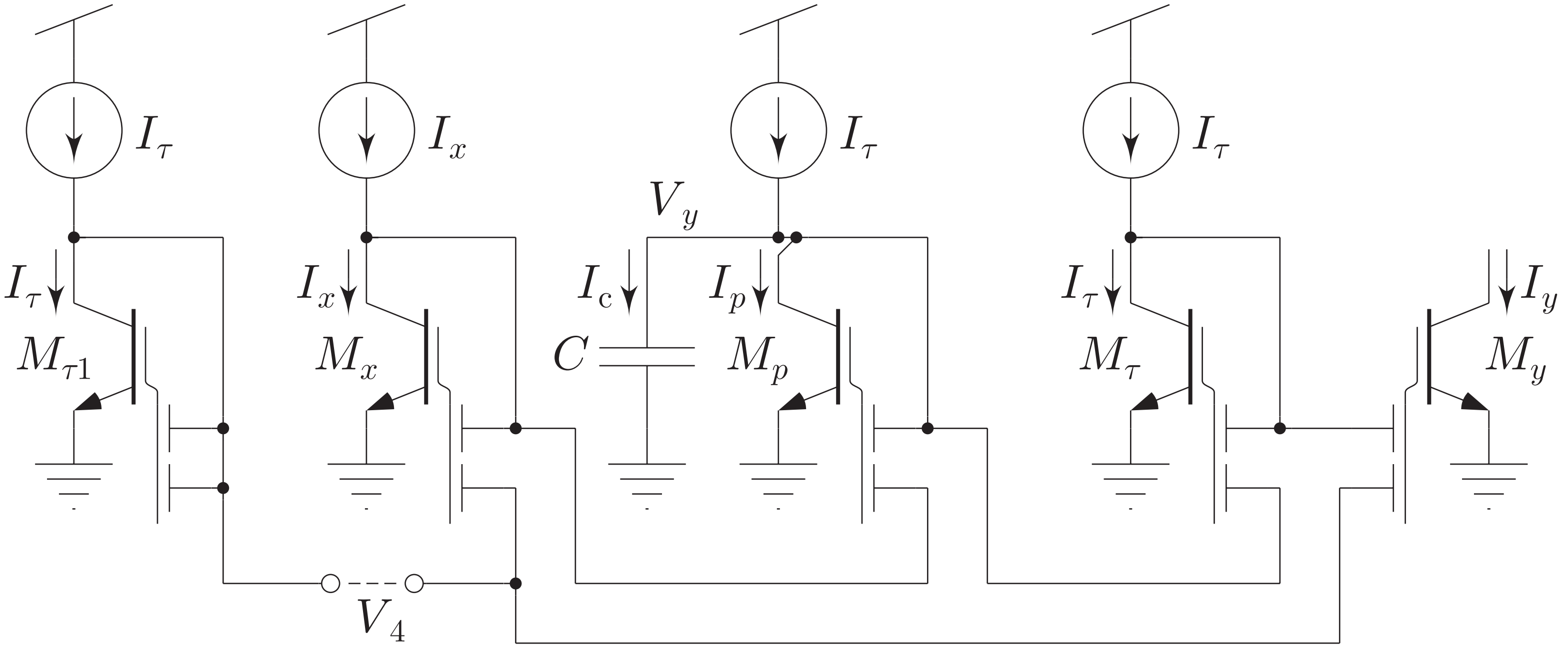

Dynamic MITE Network Synthesis: Second-Order LPF

Synthesize a second-order low-pass filter described by

$$\tau^2 \frac{d^2 y}{dt^2} + \frac{\tau}{Q} \cdot \frac{dy}{dt} + y = x, \quad \text{where} \quad x > 0.$$

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We can decompose this second-order ODE into two coupled first-order ODEs as

$$\tau \frac{d}{dt}\left(\tau \frac{dy}{dt} + \frac{y}{Q} \right) + y = x$$

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$$\tau^2 \frac{d^2 y}{dt^2} + \frac{\tau}{Q} \cdot \frac{dy}{dt} + y = x, \quad \text{where} \quad x > 0.$$

We can decompose this second-order ODE into two coupled first-order ODEs as

$$\tau \frac{d}{dt}\Bigg(\underbrace{\tau \frac{dy}{dt} + \frac{y}{Q}}_{z} \Bigg) + y = x \quad \Longrightarrow \quad \begin{cases} \tau \dfrac{dz}{dt} & = & x - y \\ \tau \dfrac{dy}{dt} & = & z - \dfrac{y}{Q}. \end{cases}$$

Dynamic MITE Network Synthesis: Second-Order LPF

We represent each signal as a ratio of a signal current to the unit current:

$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad \text{and} \quad z \equiv \frac{I_z}{I_1}.$$

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Substituting these into the pair of ODEs, we obtain

$$\begin{cases} \tau \dfrac{d}{dt}\left(\dfrac{I_z}{I_1}\right) = \dfrac{I_x}{I_1} - \dfrac{I_y}{I_1} \\ \tau \dfrac{d}{dt}\left(\dfrac{I_y}{I_1}\right) = \dfrac{I_z}{I_1} - \dfrac{1}{Q} \cdot \dfrac{I_y}{I_1} \end{cases}$$

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Dynamic MITE Network Synthesis: Second-Order LPF

To implement the time derivatives, we introduce log-compressed voltage state variables, V_z and V_y. Using the chain rule, we can express the preceding pair of equations as

$$\begin{cases} \tau \dfrac{\partial I_z}{\partial V_z} \cdot \dfrac{dV_z}{dt} & = & I_x - I_y \\ \tau \dfrac{\partial I_y}{\partial V_y} \cdot \dfrac{dV_y}{dt} & = & I_z - \dfrac{I_y}{Q} \end{cases}$$

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$$\Longrightarrow \begin{cases} \dfrac{w\tau}{U_{\mathrm{T}}} \cdot \dfrac{dV_z}{dt} = \dfrac{I_y}{I_z} - \dfrac{I_x}{I_z} \\ \dfrac{w\tau}{U_{\mathrm{T}}} \cdot \dfrac{dV_y}{dt} = \dfrac{1}{Q} - \dfrac{I_z}{I_y} \end{cases}$$

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Dynamic MITE Network Synthesis: Second-Order LPF

By introducing

$$I_\tau \equiv \frac{CU_\mathrm{T}}{w\tau}, \quad I_{cz} \equiv C\frac{dV_z}{dt}, \quad \text{and} \quad I_{cy} \equiv C\frac{dV_y}{dt},$$

we can express this pair of equations as

$$\begin{cases} \dfrac{I_{cz}}{I_\tau} = \dfrac{I_y}{I_z} - \dfrac{I_x}{I_z} \\ \dfrac{I_{cy}}{I_\tau} = \dfrac{1}{Q} - \dfrac{I_z}{I_y} \end{cases}$$

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where we have further introduced

$$I_w \equiv \frac{I_y I_\tau}{I_z}, \quad I_{pz} \equiv \frac{I_x I_\tau}{I_z}, \quad \text{and} \quad I_{py} \equiv \frac{I_z I_\tau}{I_y}.$$

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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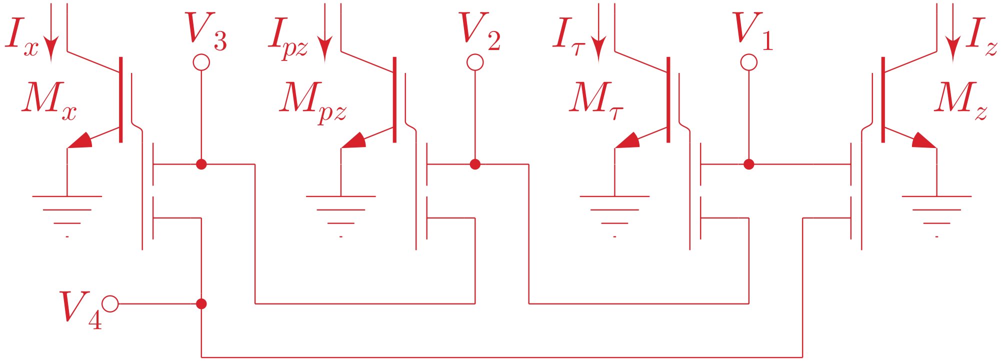

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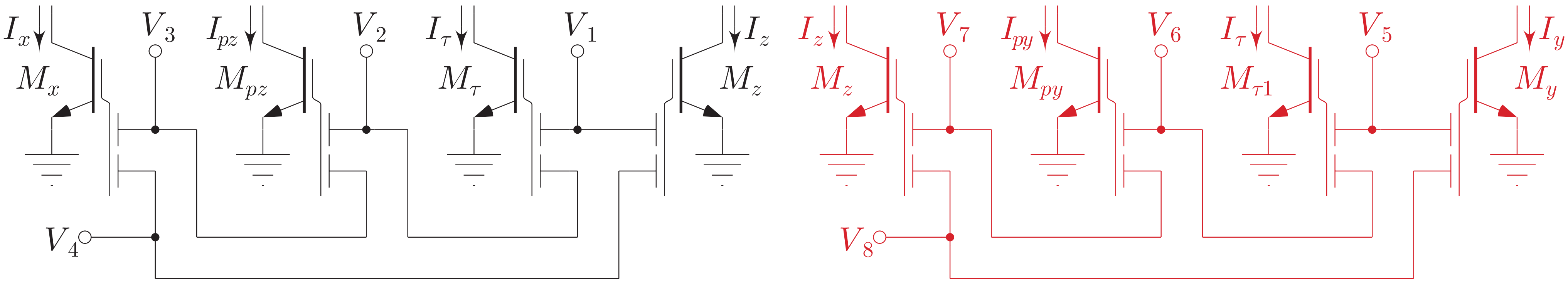

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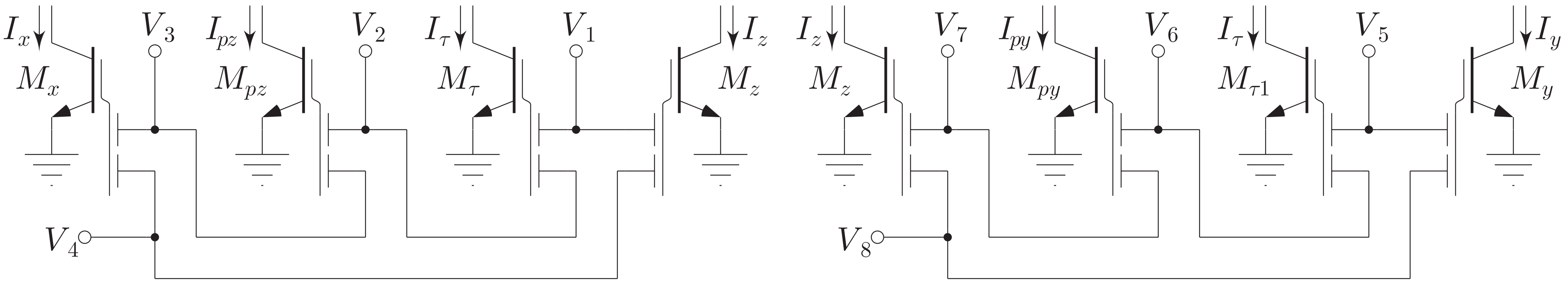

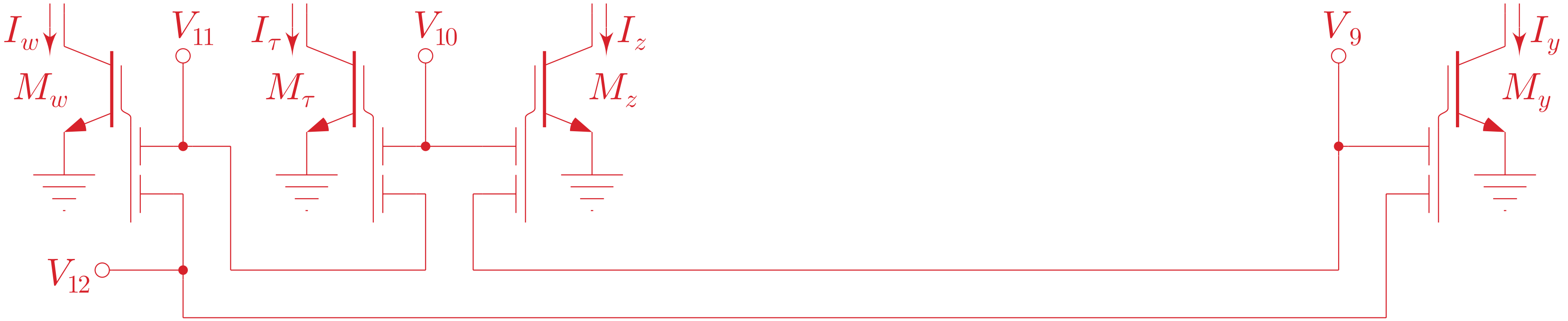

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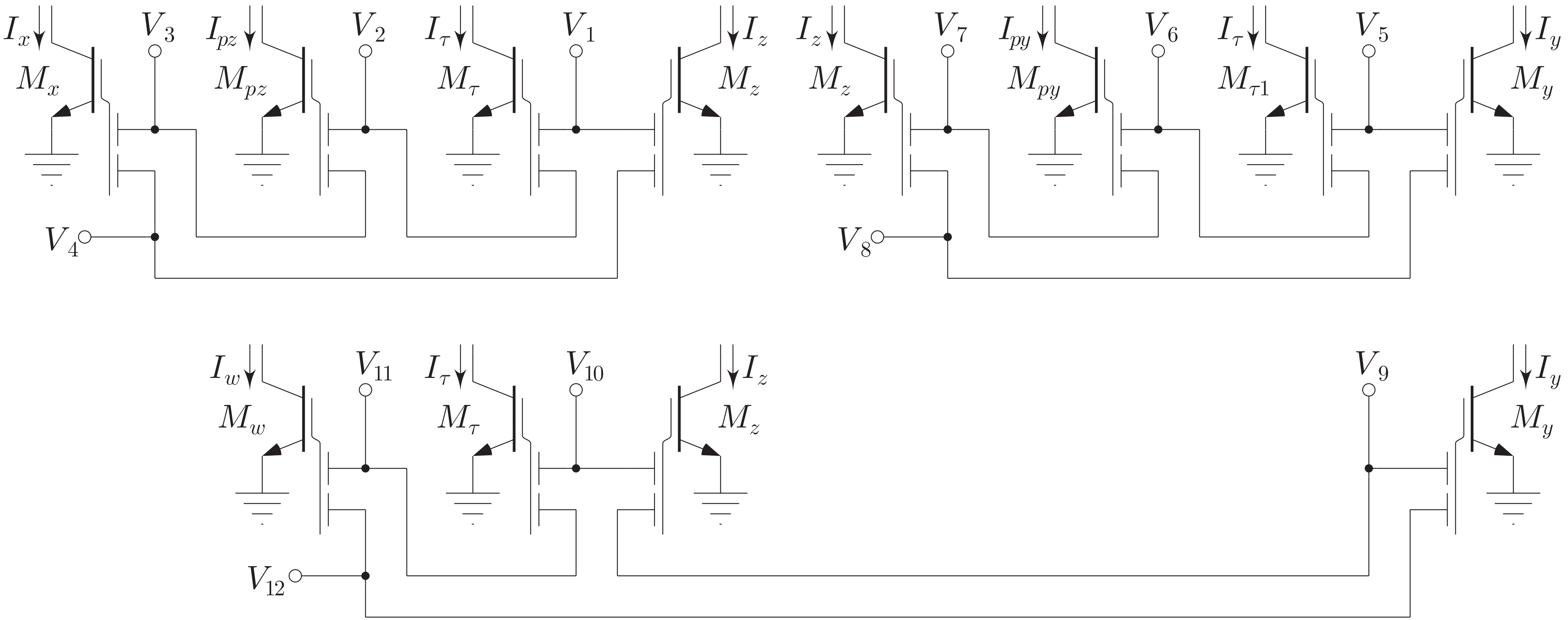

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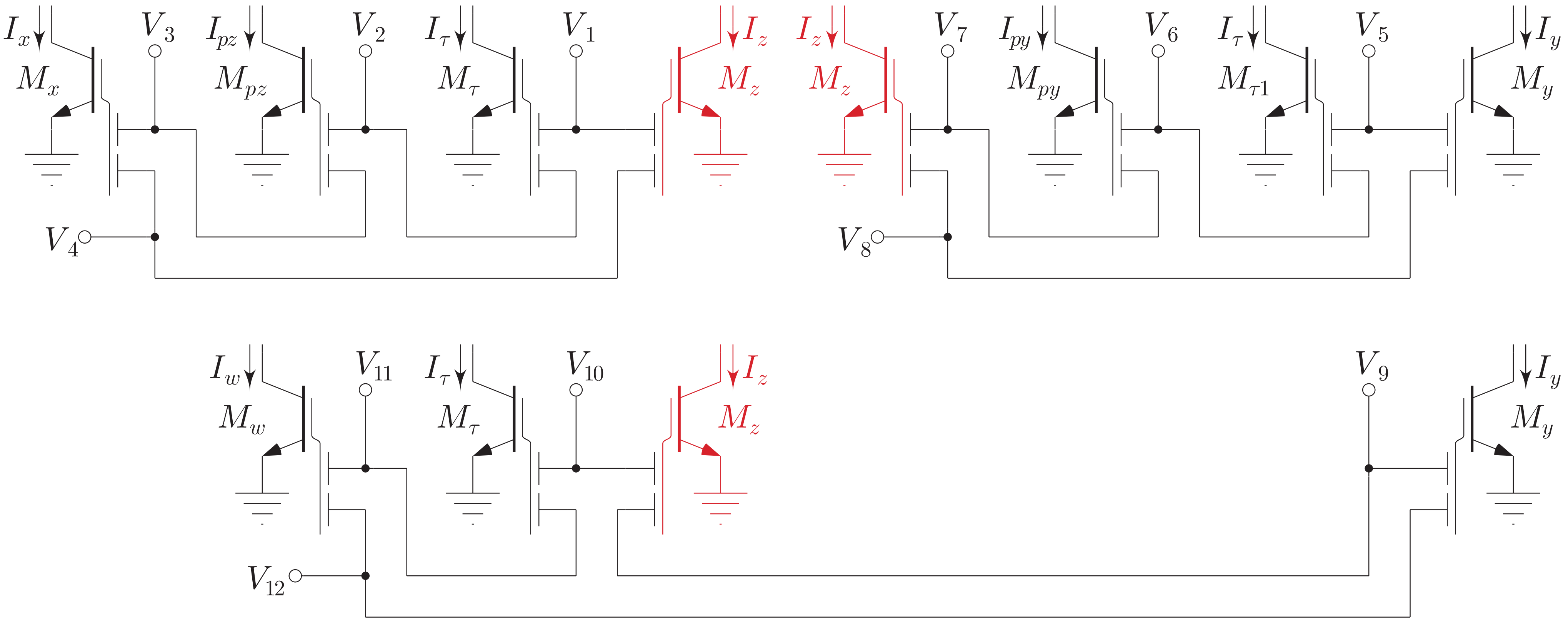

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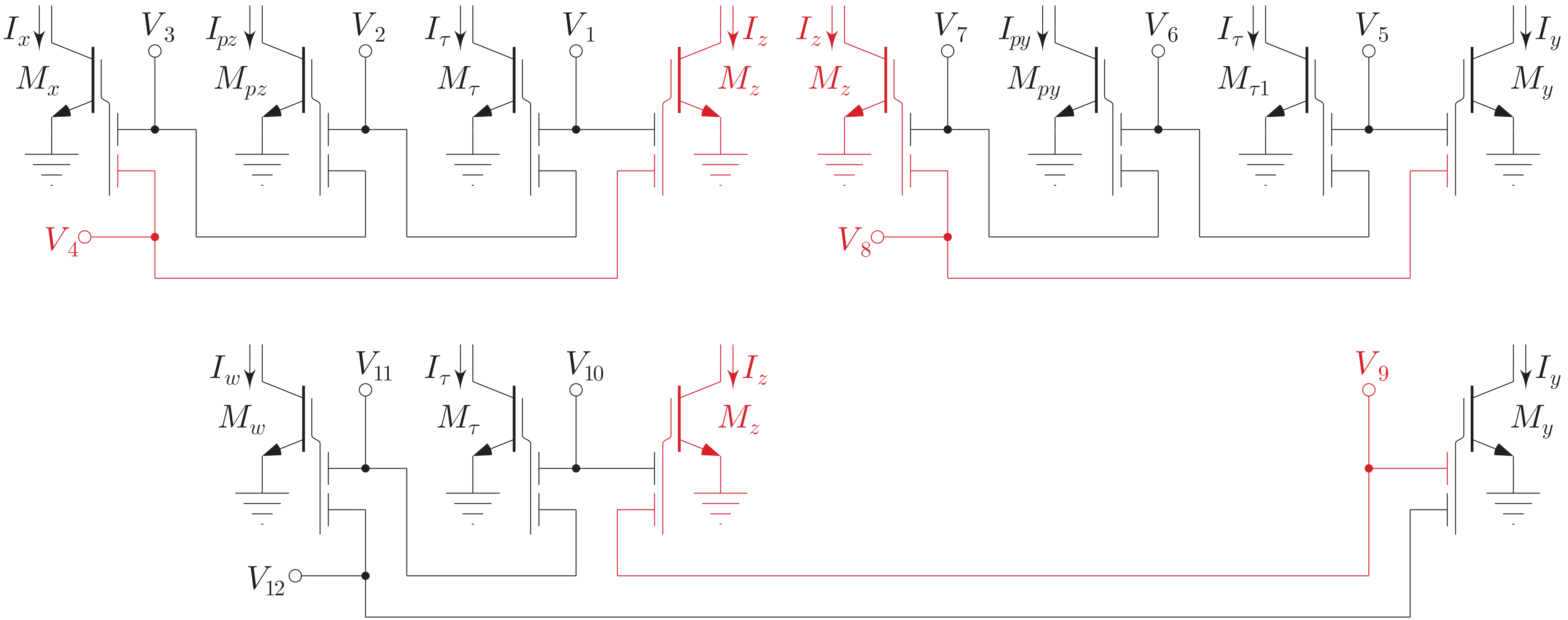

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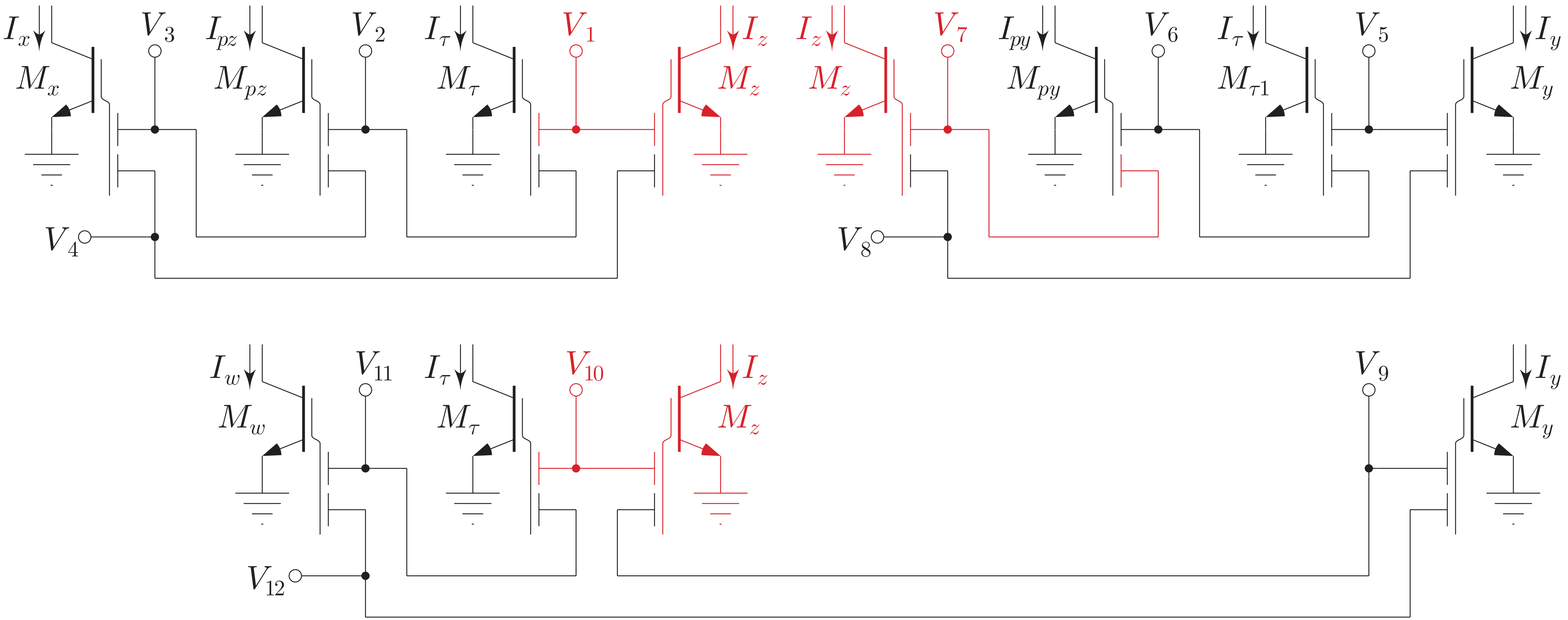

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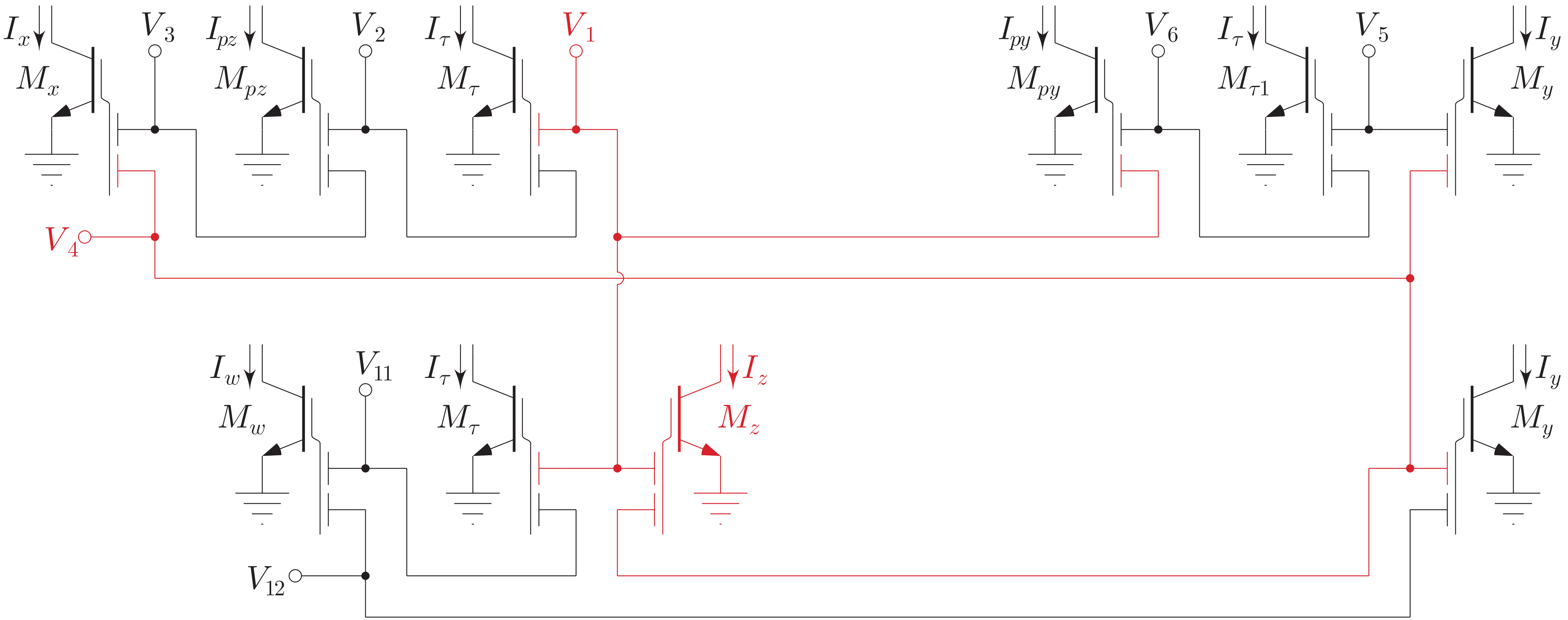

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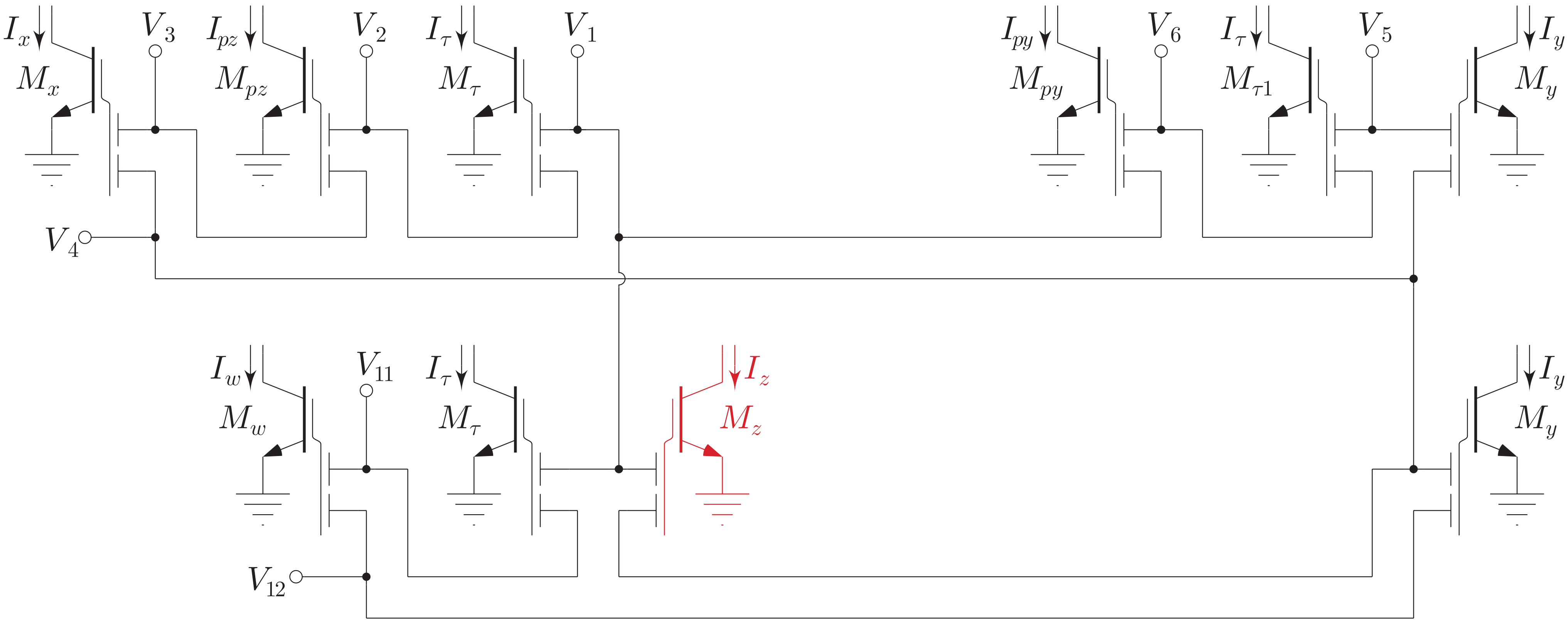

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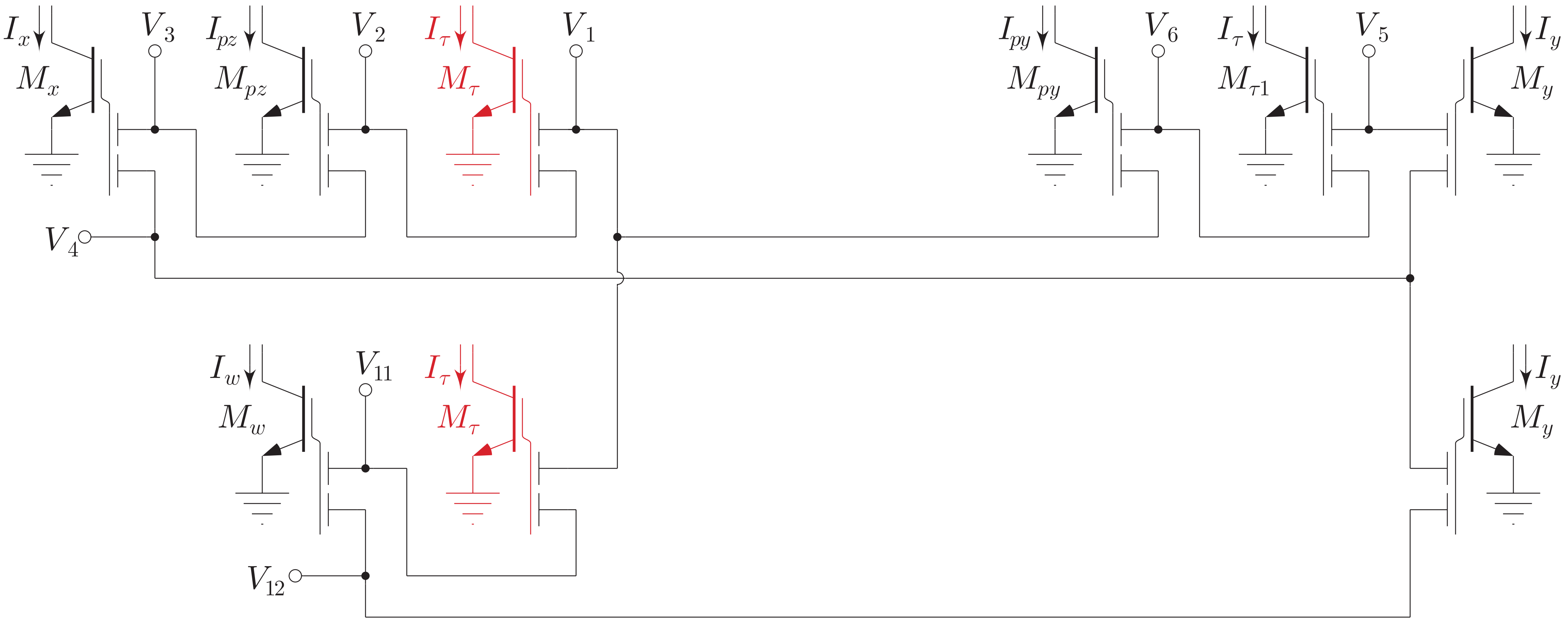

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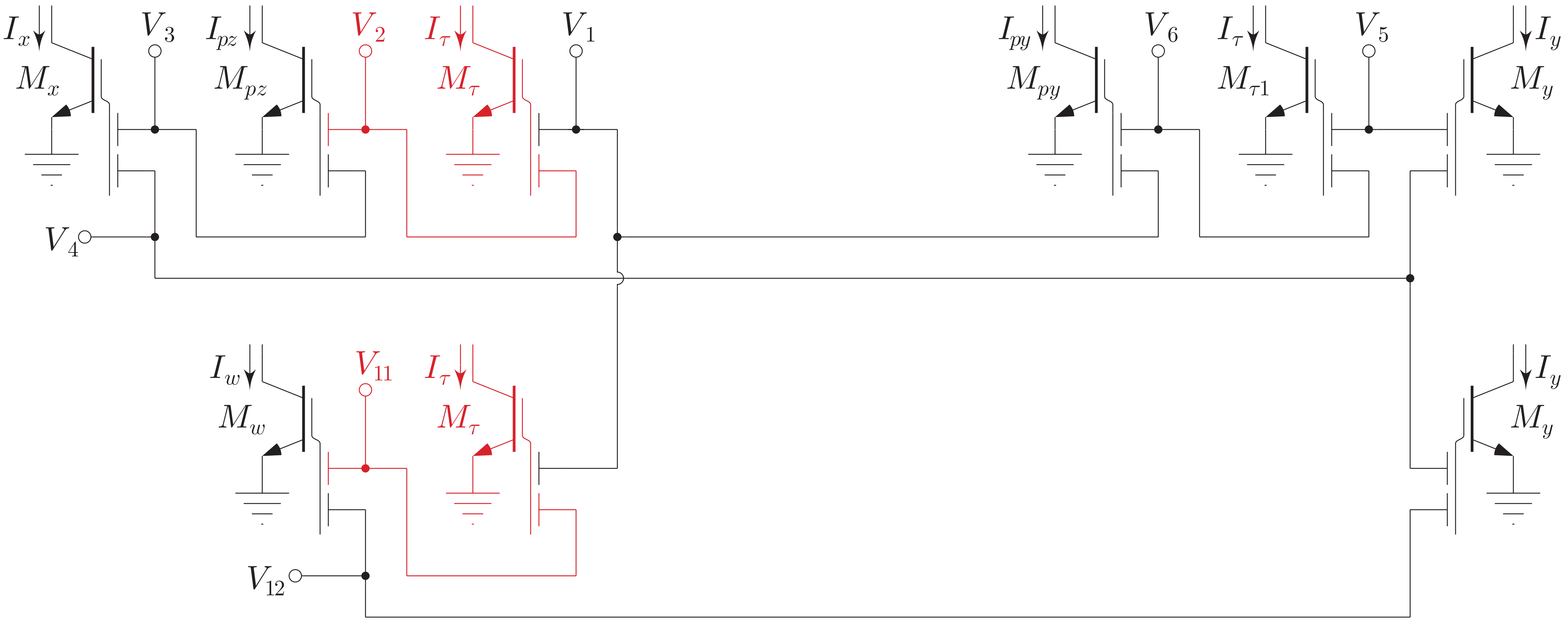

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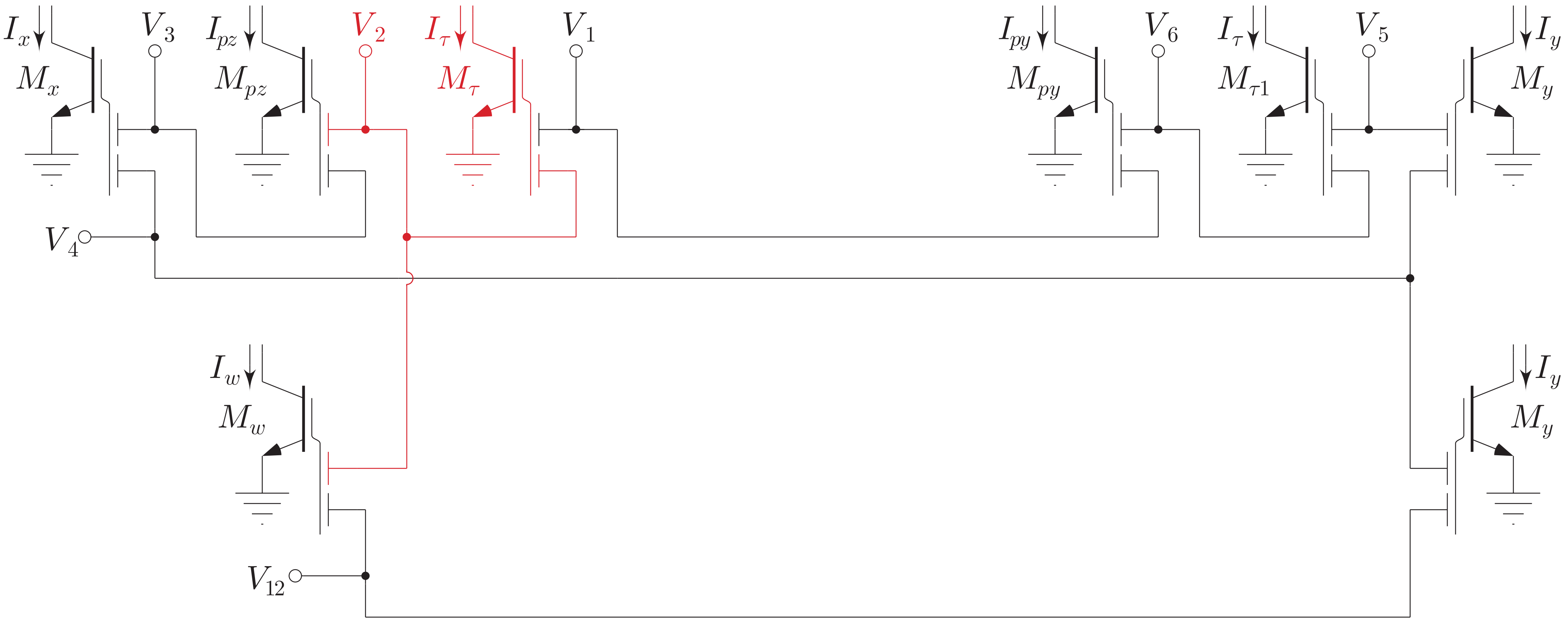

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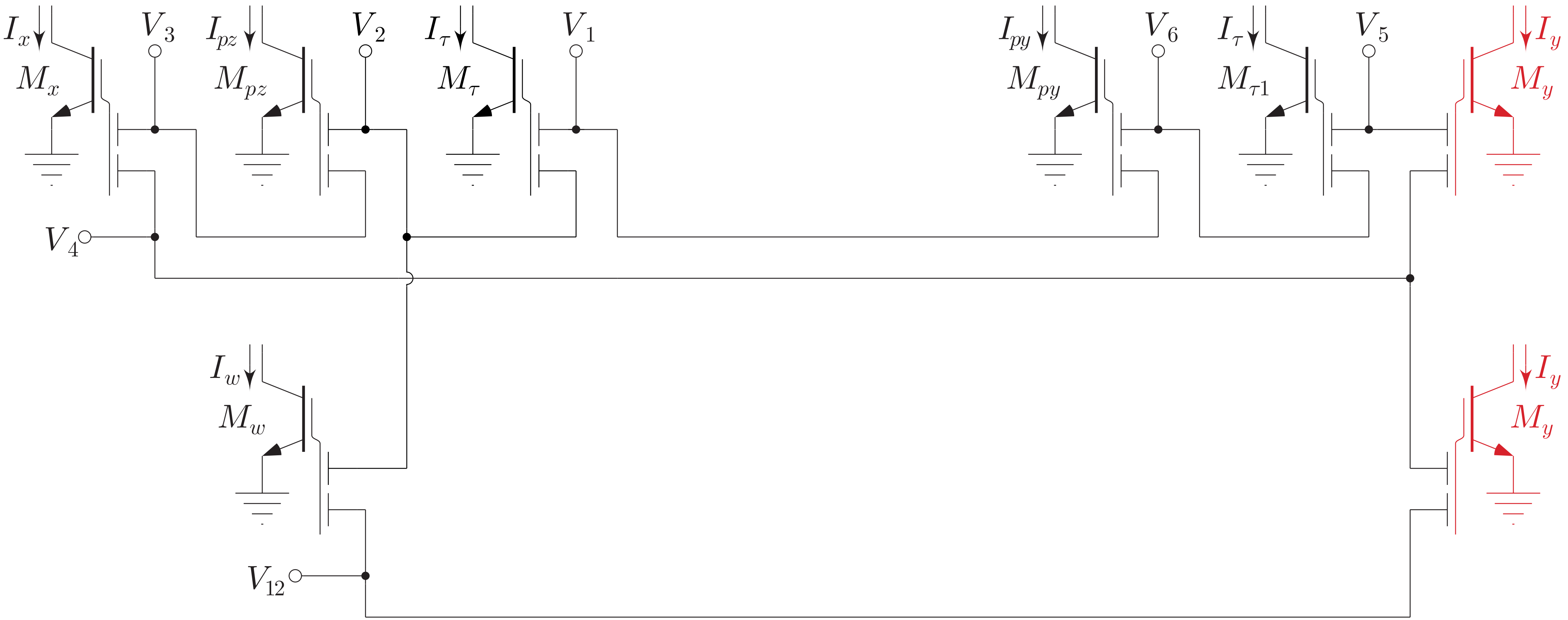

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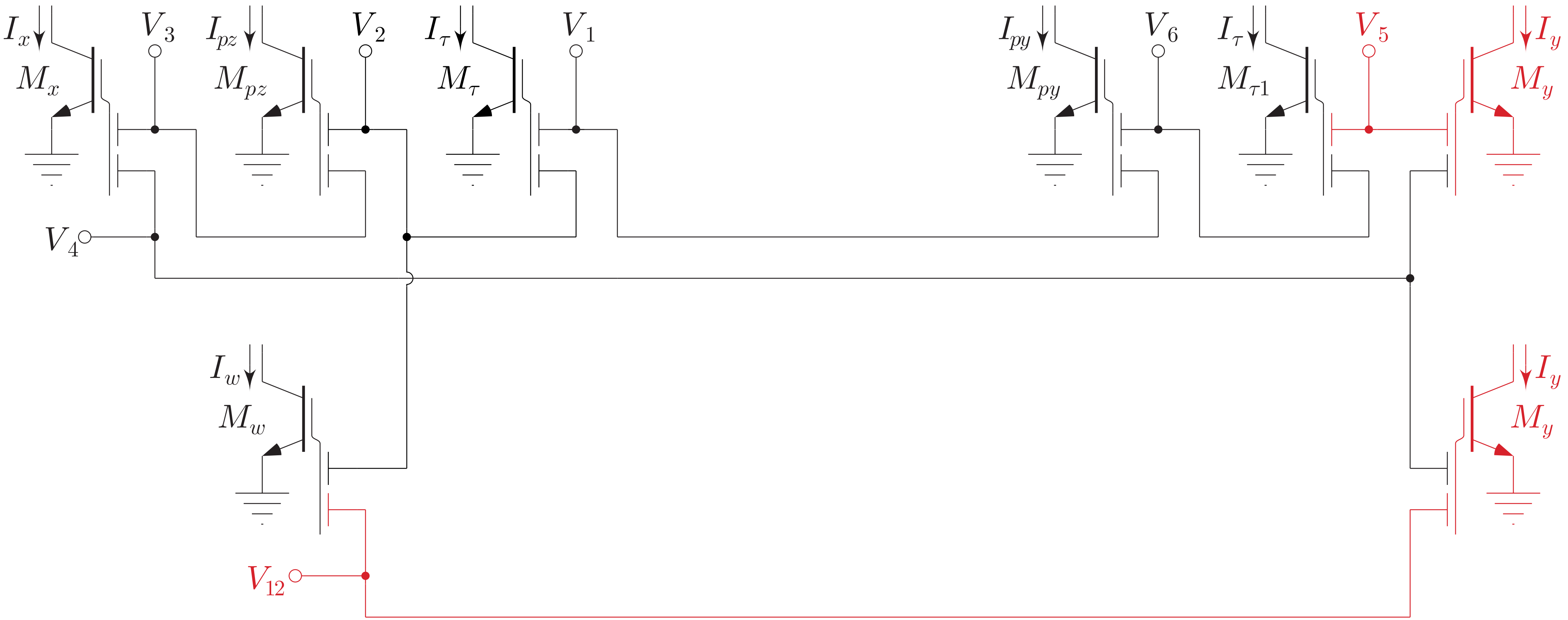

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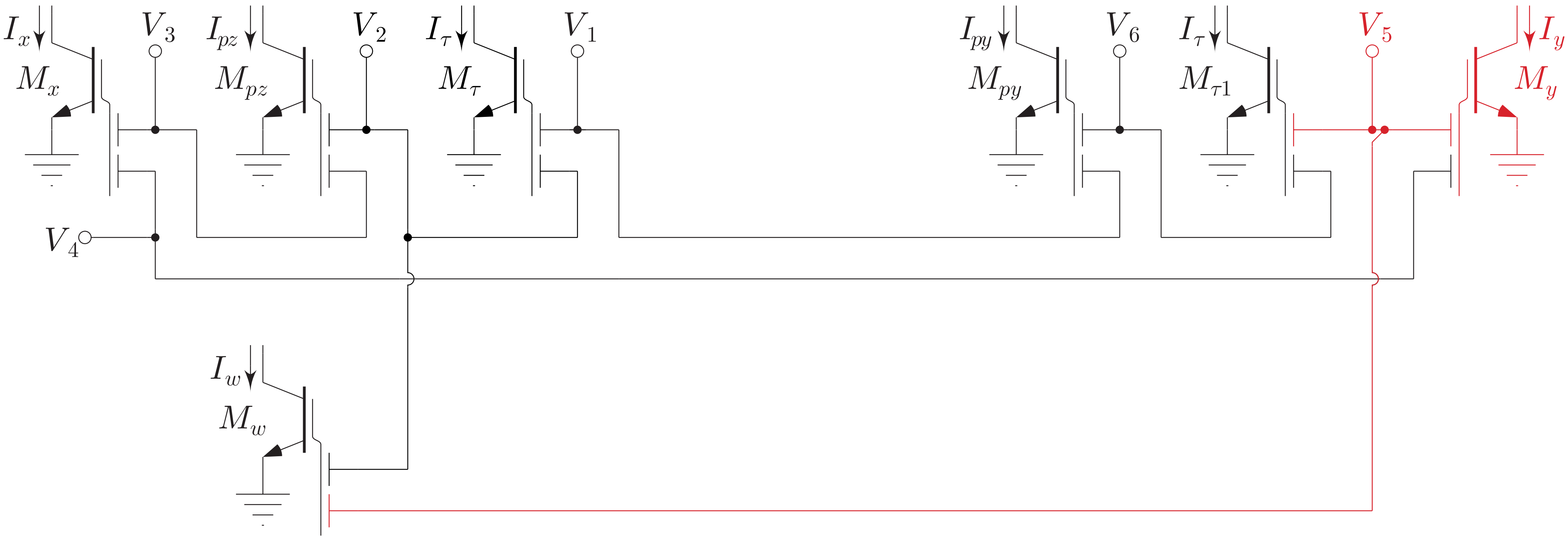

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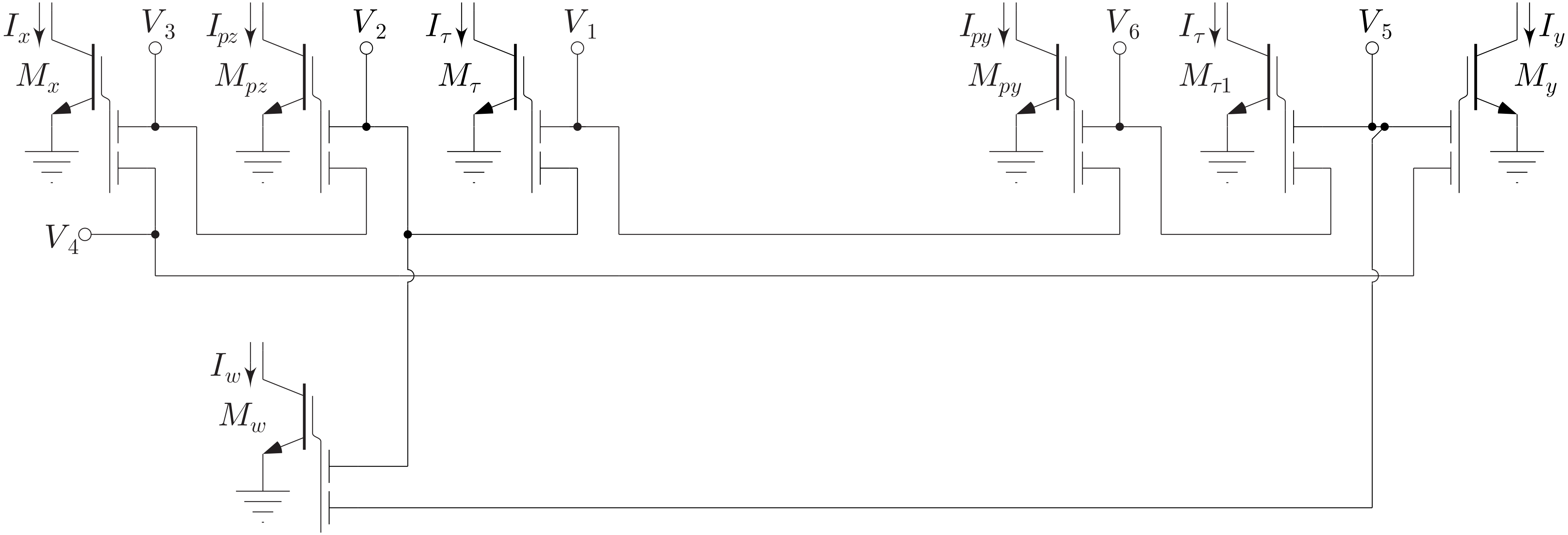

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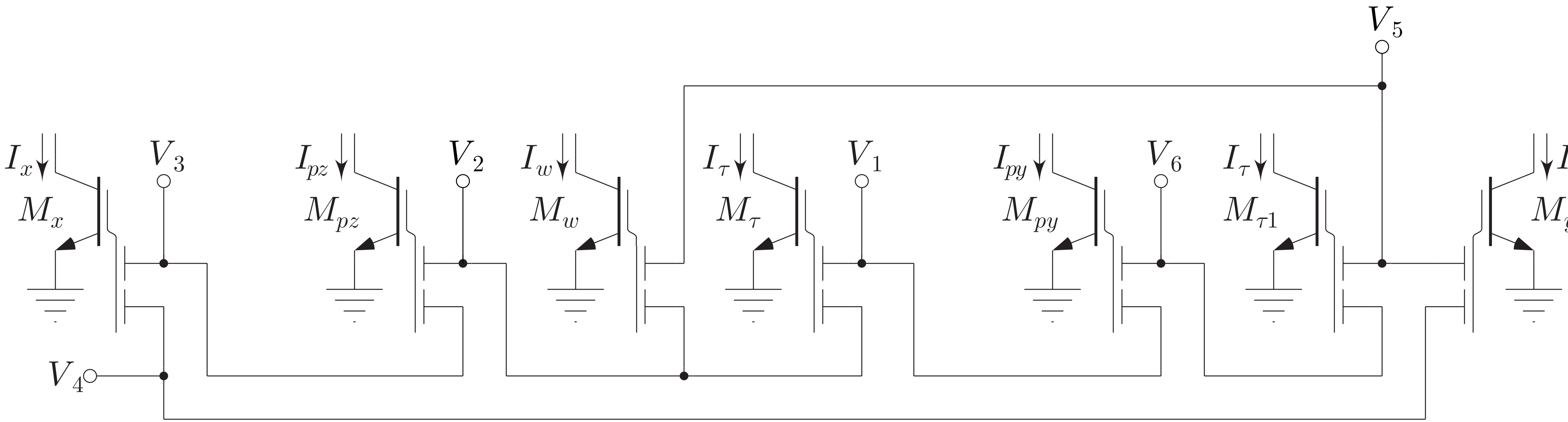

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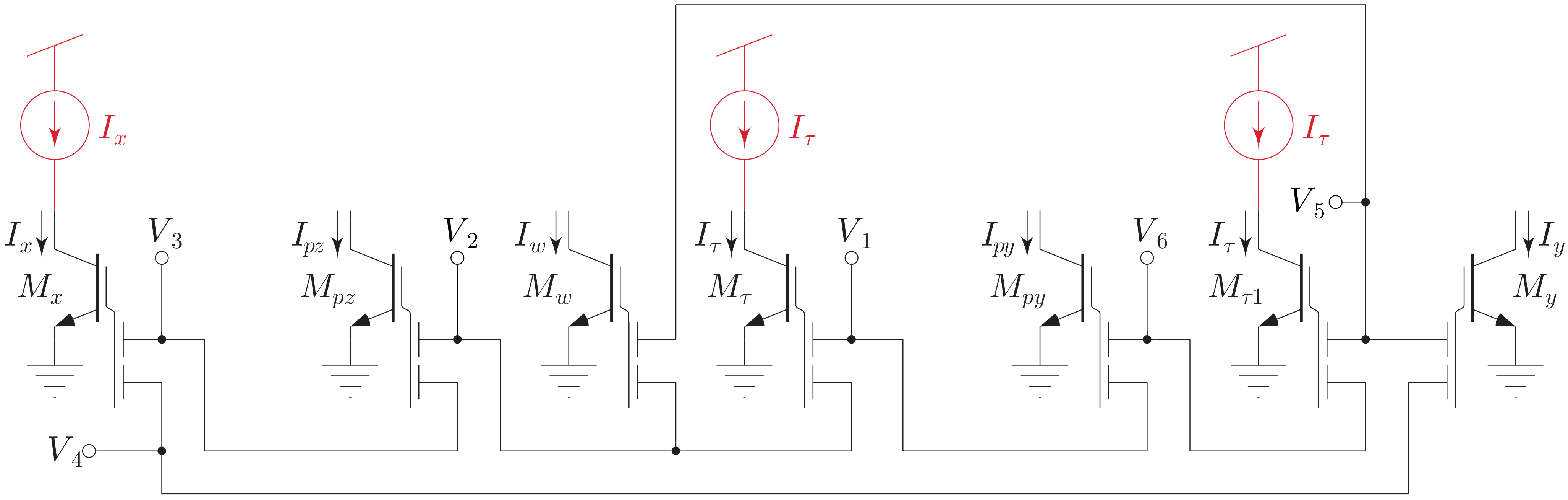

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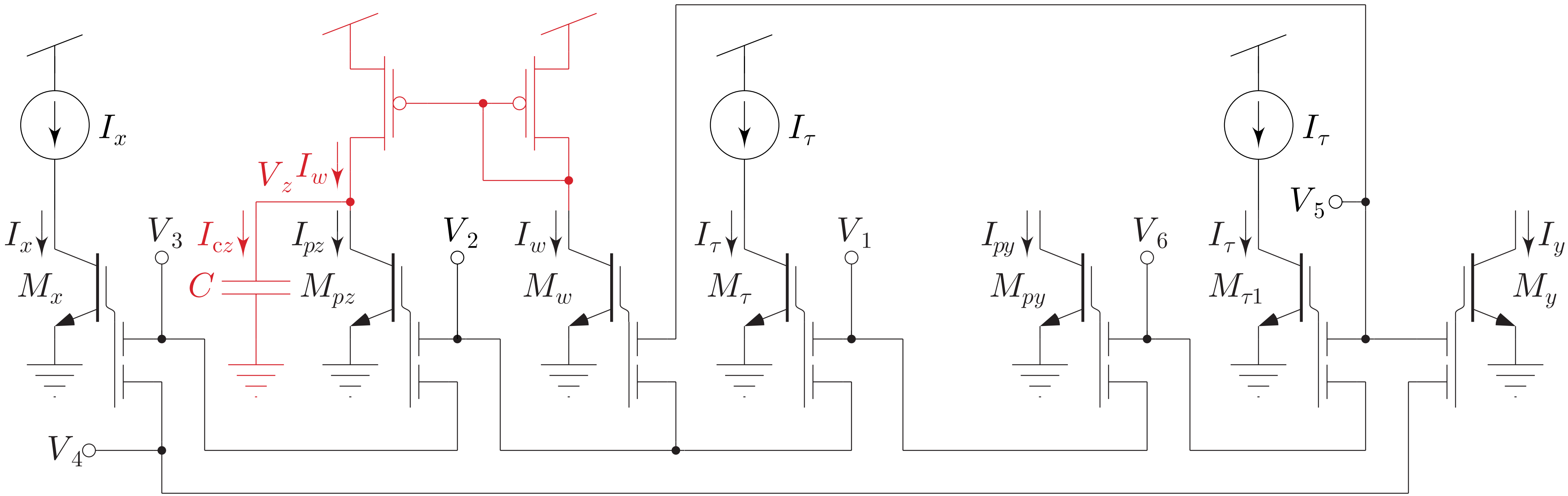

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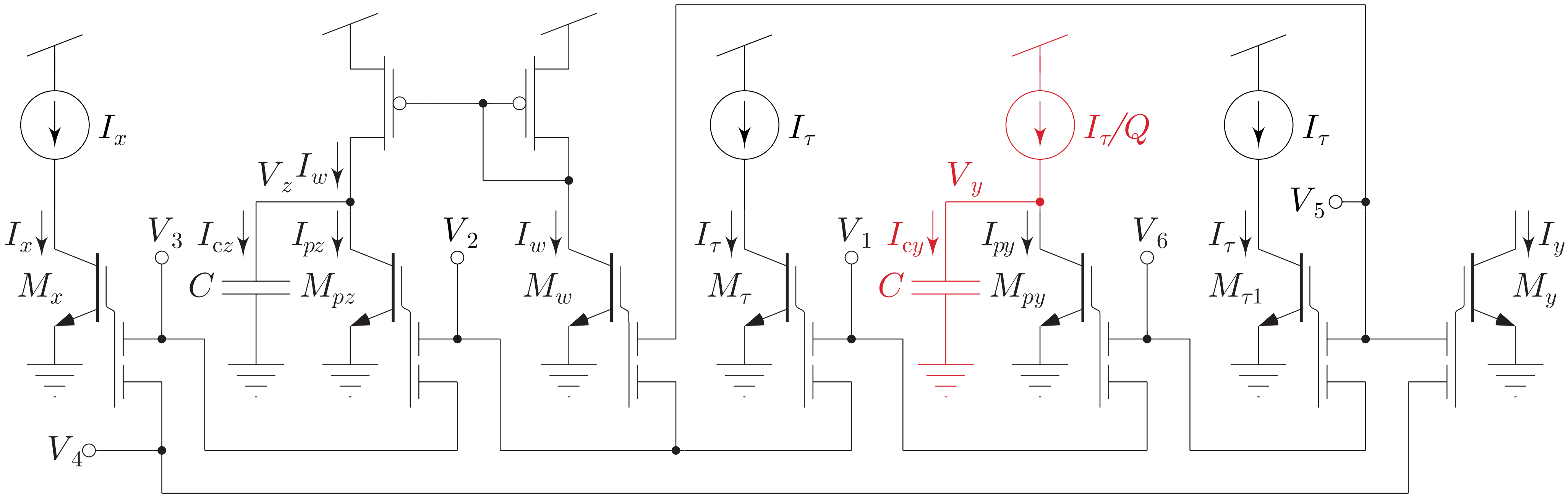

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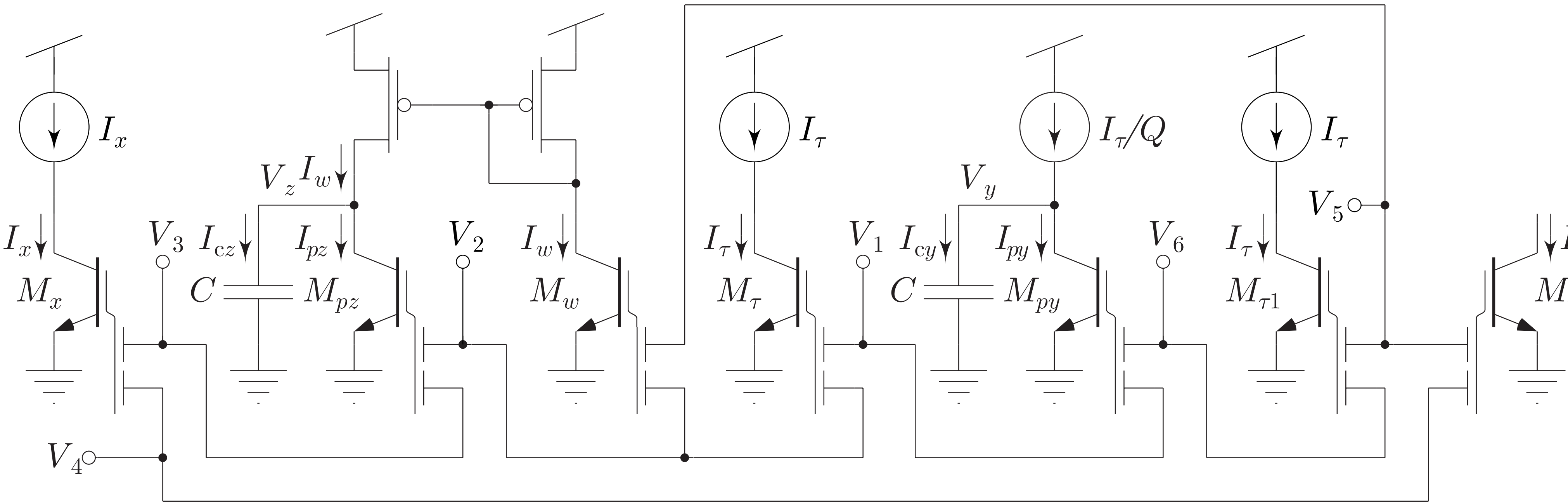

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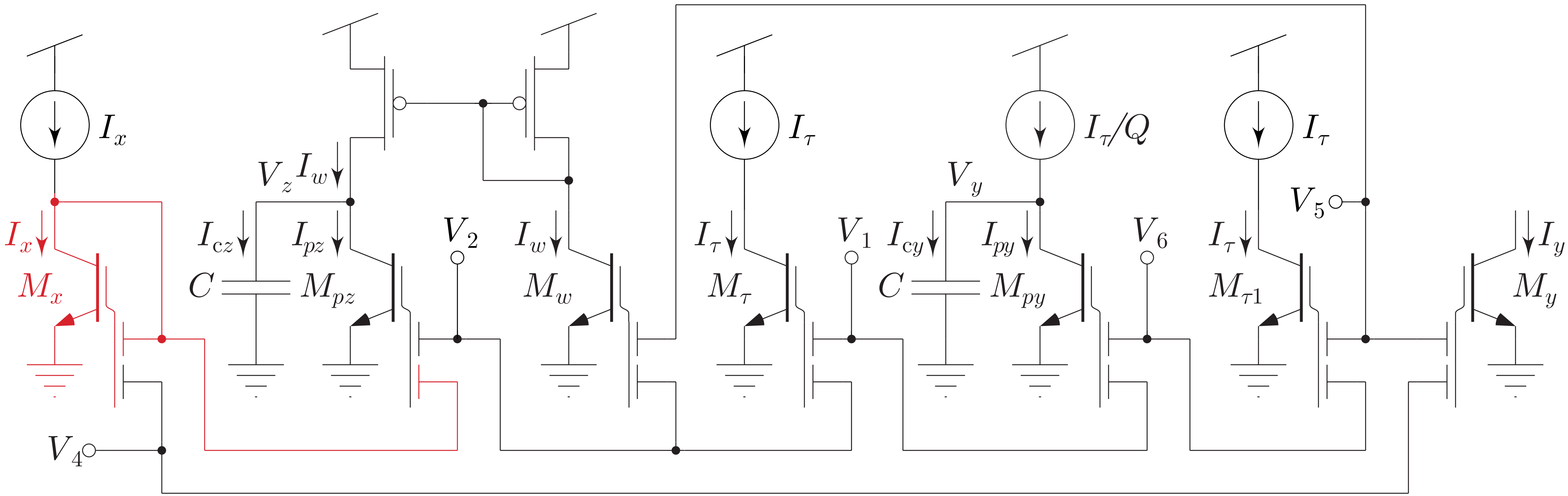

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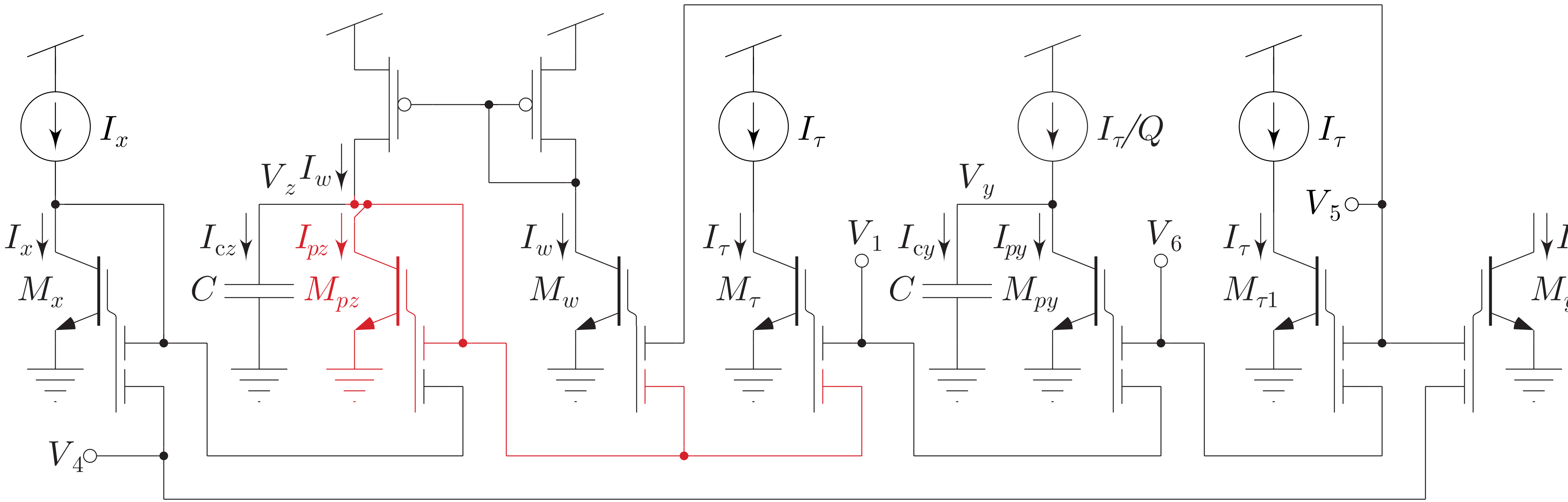


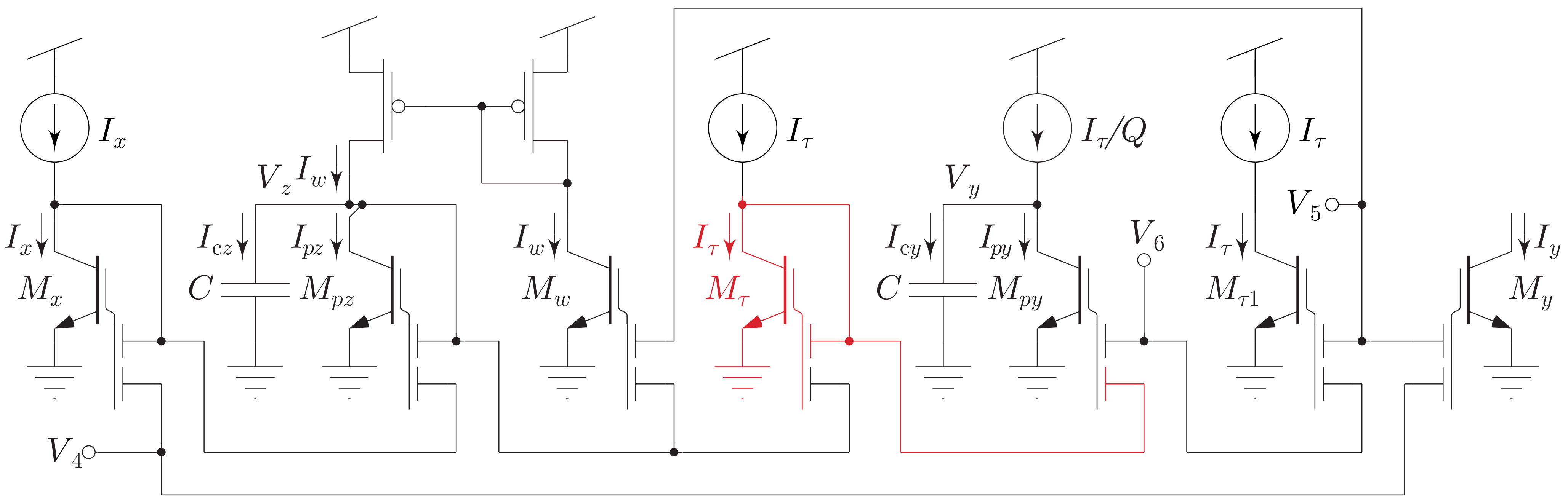
Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

$I_z I_w = I_y I_\tau$

KCL: $I_{pz} + I_{cz} = I_w$

$I_{py} + I_{cy} = I_\tau / Q$



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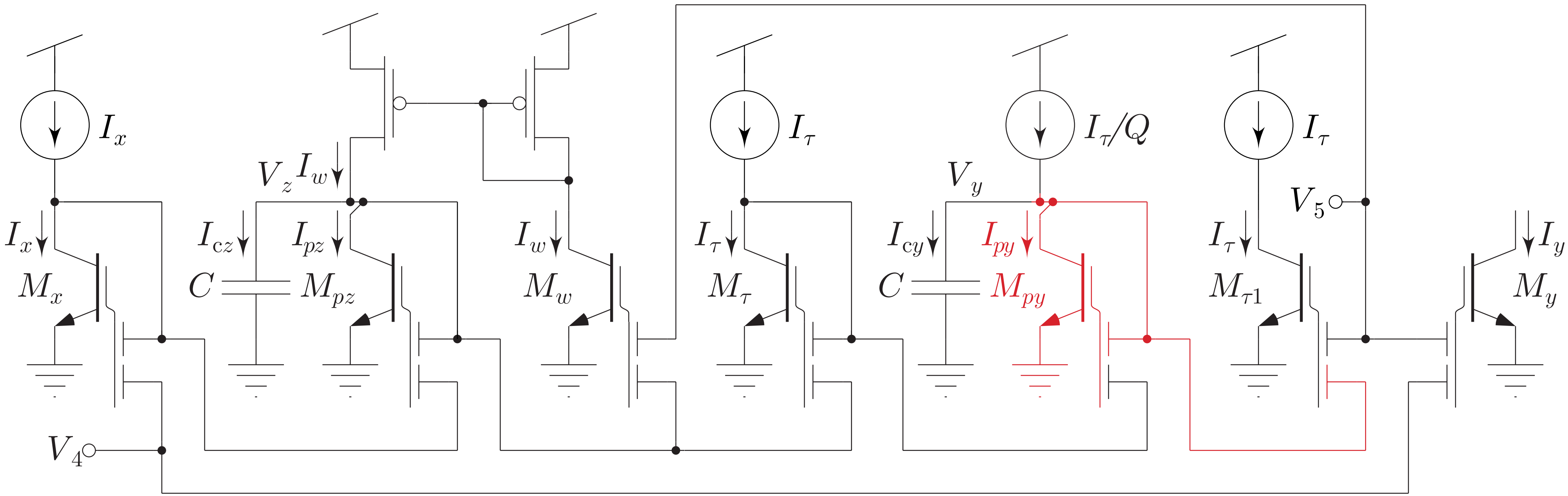

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau \qquad I_y I_{py} = I_z I_\tau$

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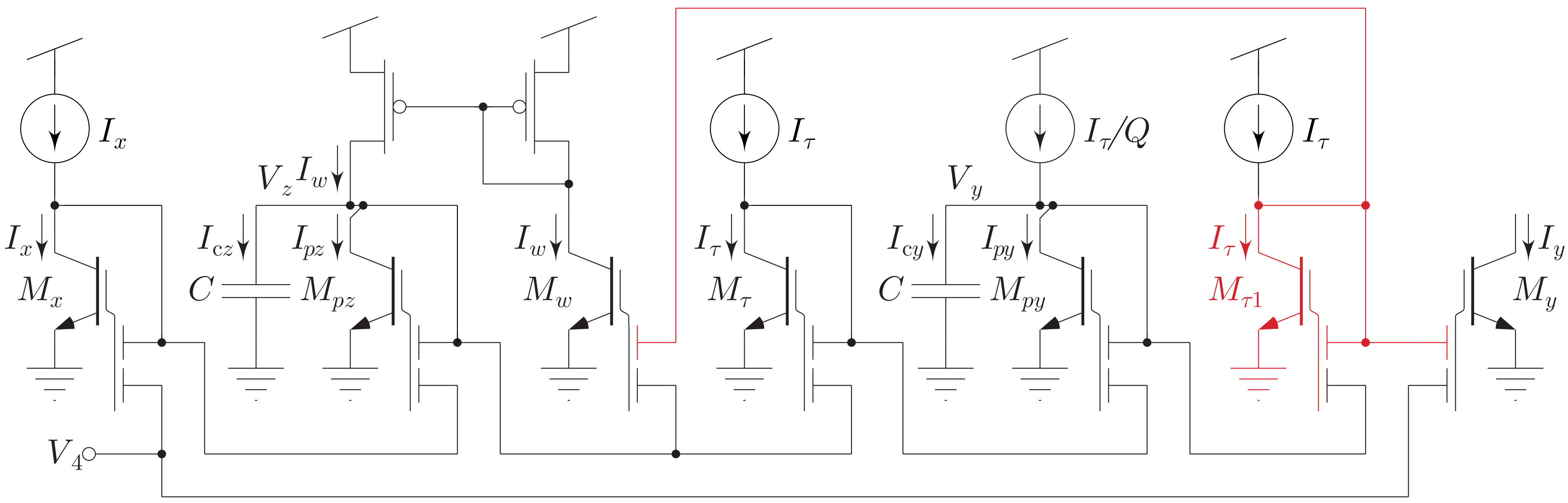

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$

$I_z I_w = I_y I_\tau$

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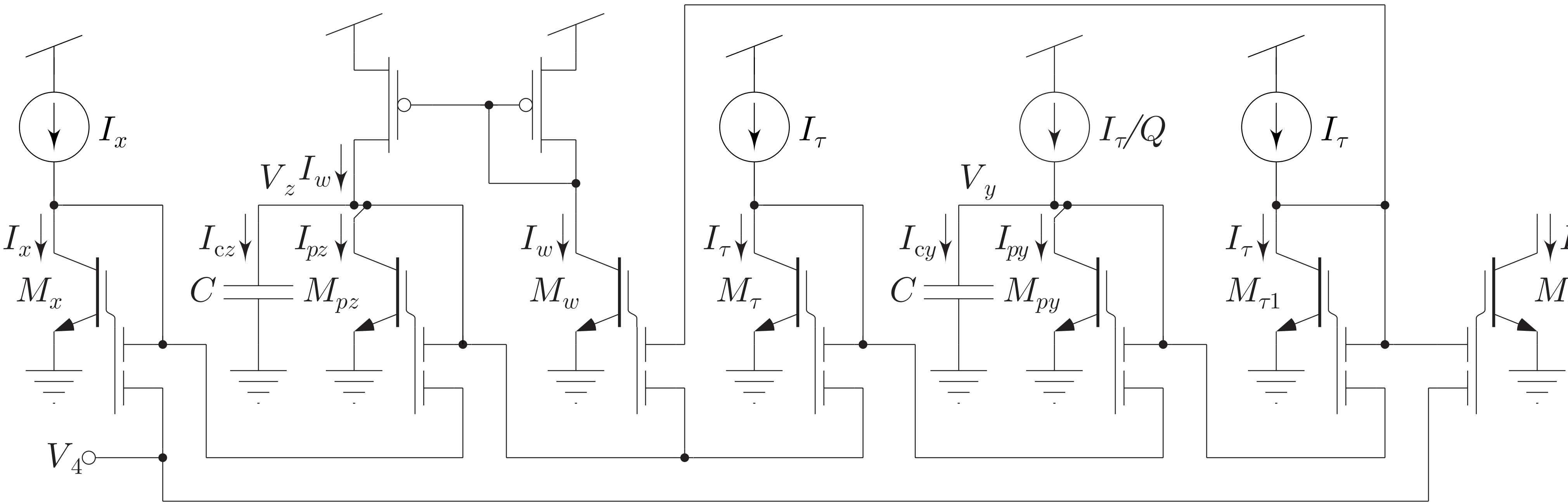

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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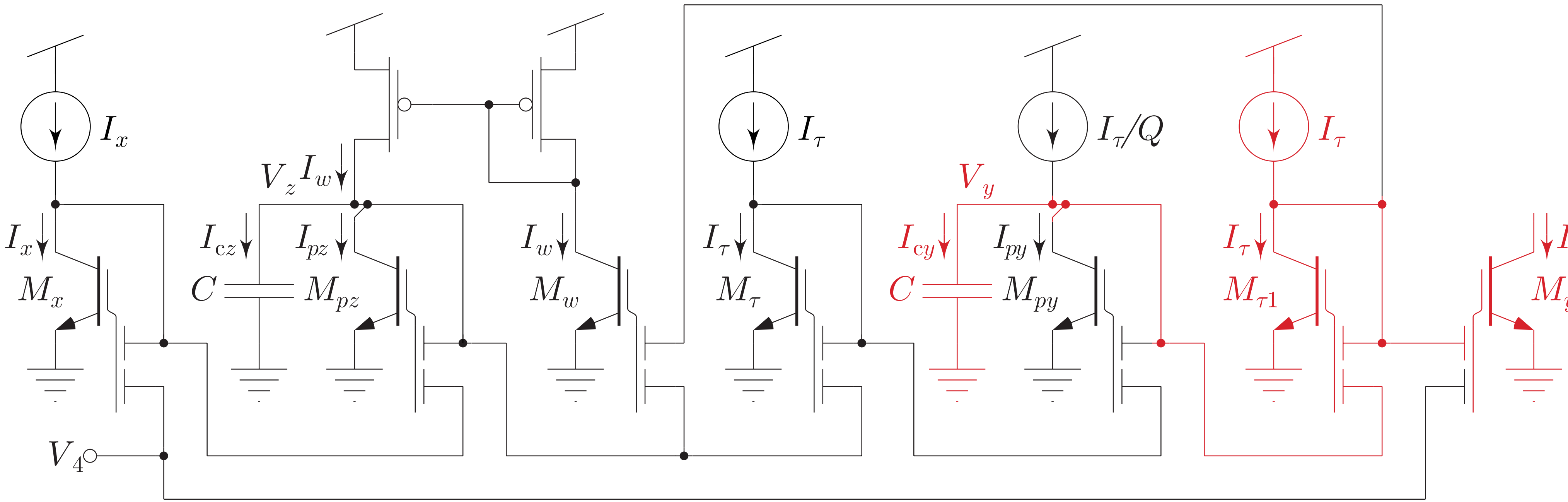

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$ $\quad I_z I_w = I_y I_\tau$

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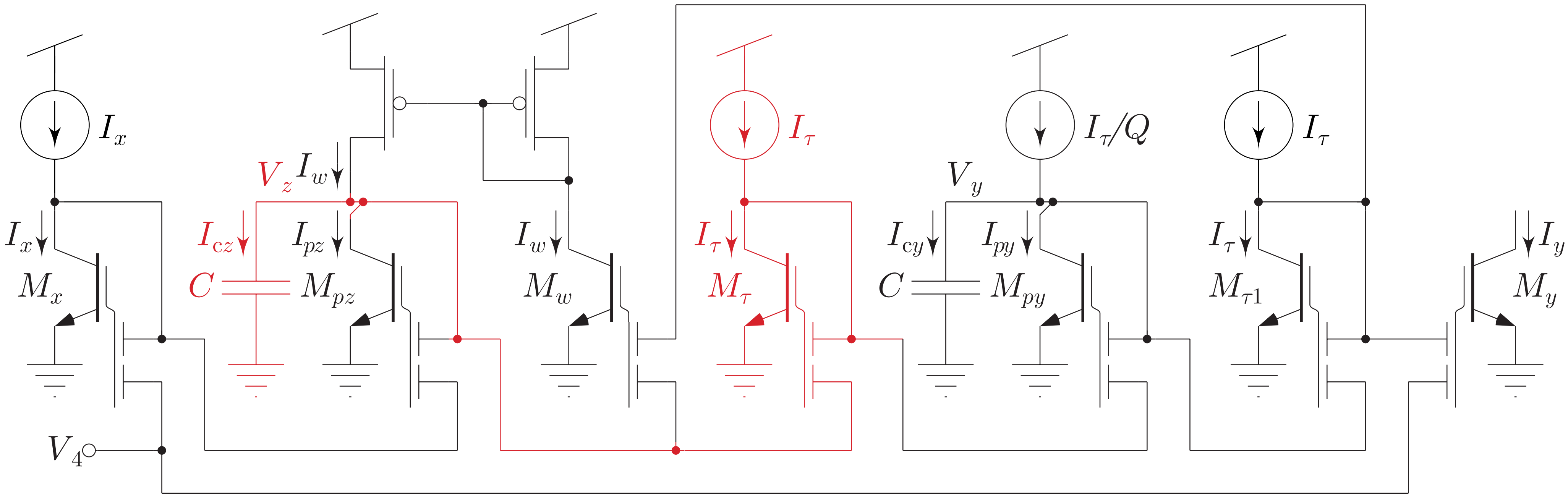

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