Synthesis of Static and Dynamic MITE Networks

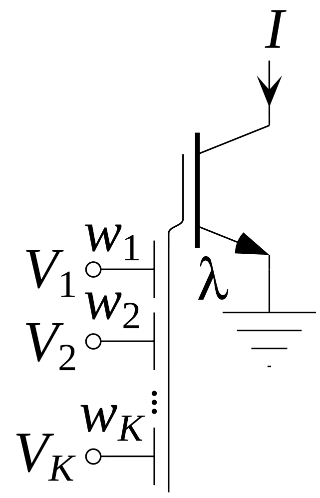
Bradley A. Minch

Mixed Analog-Digital VLSI Circuits and Systems Laboratory
School of Electrical and Computer Engineering
Cornell University
Ithaca, NY 14853–5401

minch@ece.cornell.edu
http://www.ece.cornell.edu/~minch

The Multiple-Input Translinear Element

$$\boxed{I = \lambda I_s \exp\left[\sum_{k=1}^{K} \frac{w_k V_k}{U_T}\right]}$$



- The MITE has K *trans*conductances, each of which is *linear* in the output current, I:

$$g_k = \frac{\partial I}{\partial V_k}$$

$$= \frac{w_k}{U_T} \lambda I_s \exp\left[\sum_{k=1}^{K} \frac{w_k V_k}{U_T}\right]$$

$$= \frac{w_k}{U_T} I$$

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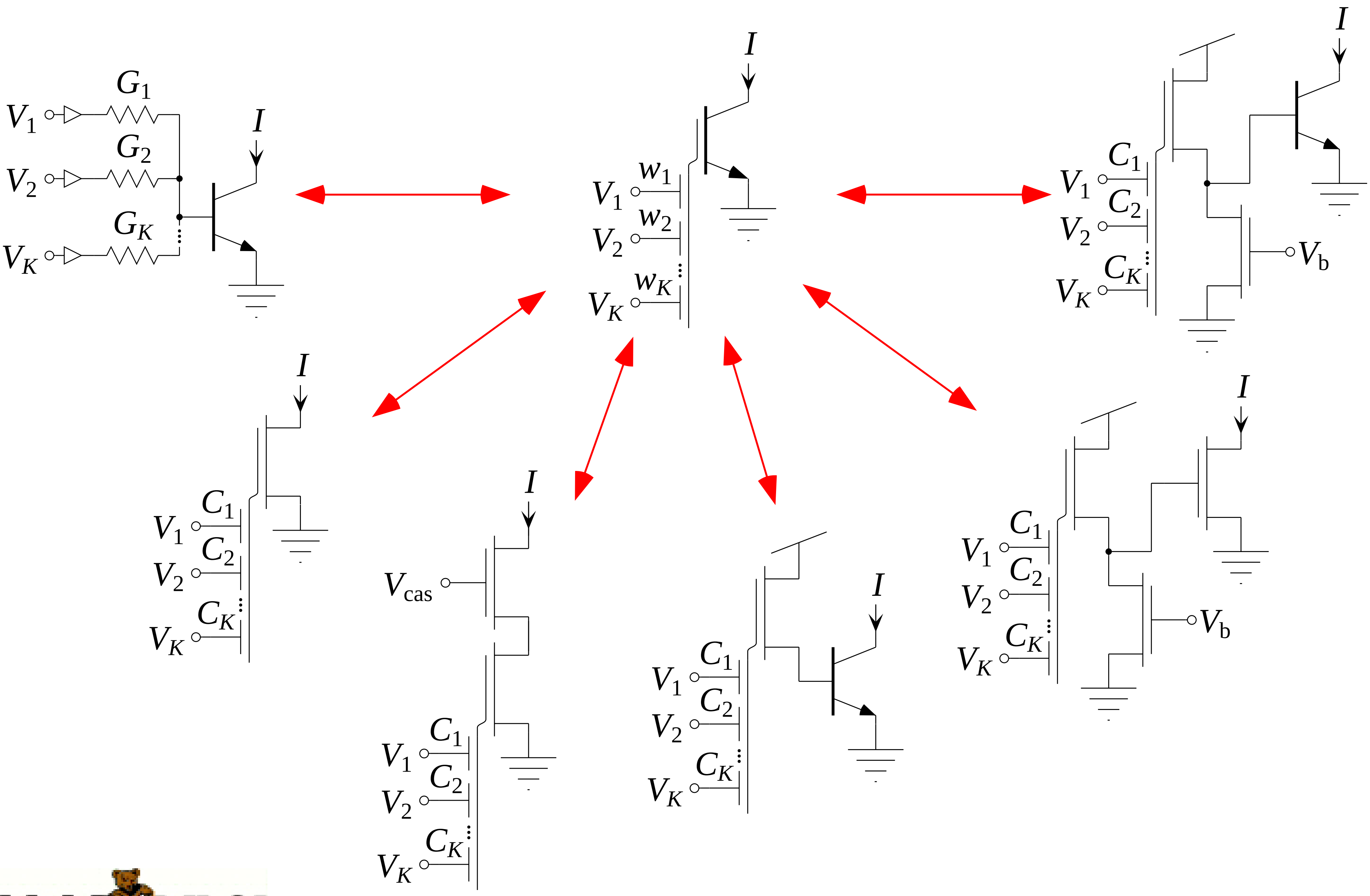
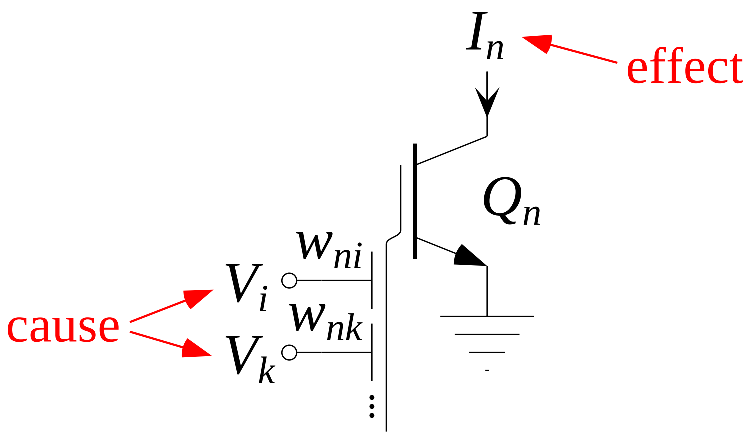
MITE Implementations



Basic MITE Configurations: Voltage-In, Current-Out

$$I_n \propto \exp\left[\frac{w_{ni}V_i + w_{nk}V_k + \ldots}{U_T}\right]$$

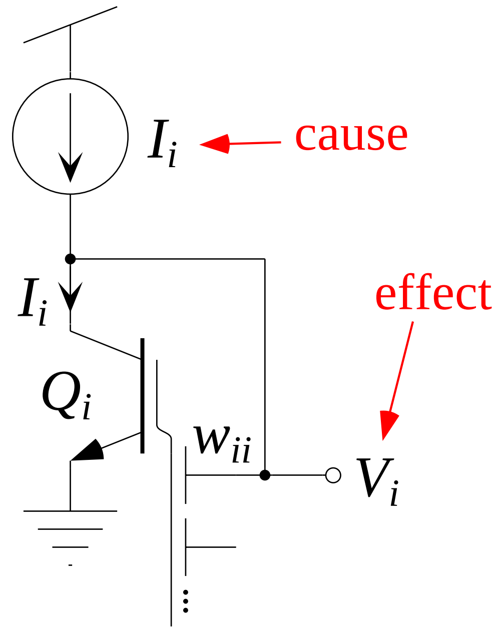
$$\Rightarrow \boxed{I_n \propto \exp\left[\frac{w_{ni}V_i}{U_T}\right]\exp\left[\frac{w_{nk}V_k}{U_T}\right]}$$



Basic MITE Configurations: Current-In, Voltage-Out

$$I_i \propto \exp\left[\frac{w_{ii} V_i + \dots}{U_T}\right]$$

$$\Rightarrow \boxed{V_i = \frac{U_T}{w_{ii}} \log I_i - \dots}$$



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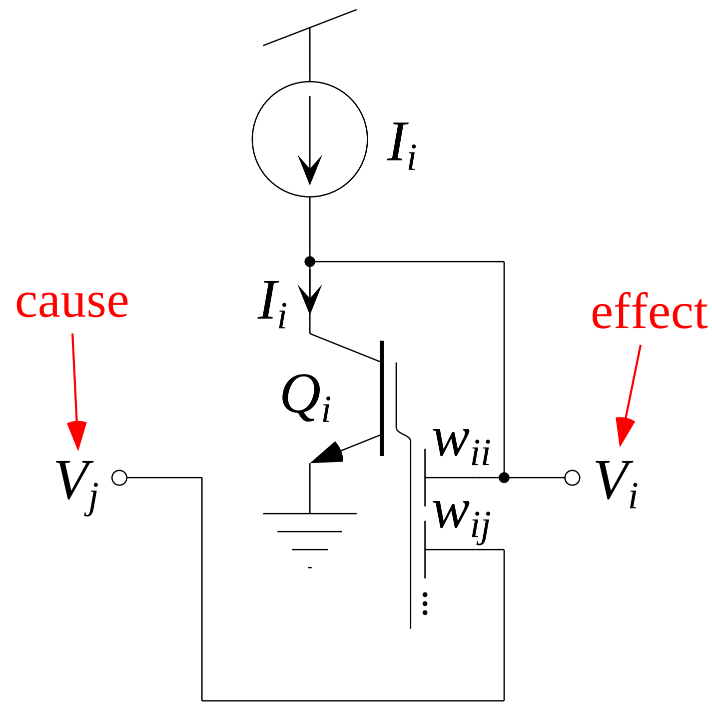
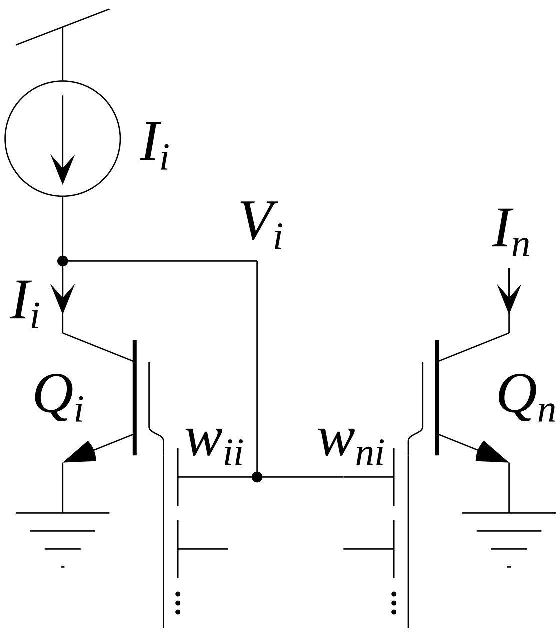
Basic MITE Configurations: Voltage-In, Voltage-Out

$$I_i \propto \exp\left[\frac{w_{ii} V_i + w_{ij} V_j + \ldots}{U_T}\right]$$

$$\Rightarrow \boxed{V_i = \frac{U_T}{w_{ii}} \log I_i - \frac{w_{ij}}{w_{ii}} V_j - \ldots}$$



Static MITE Networks: Power-Law Circuits



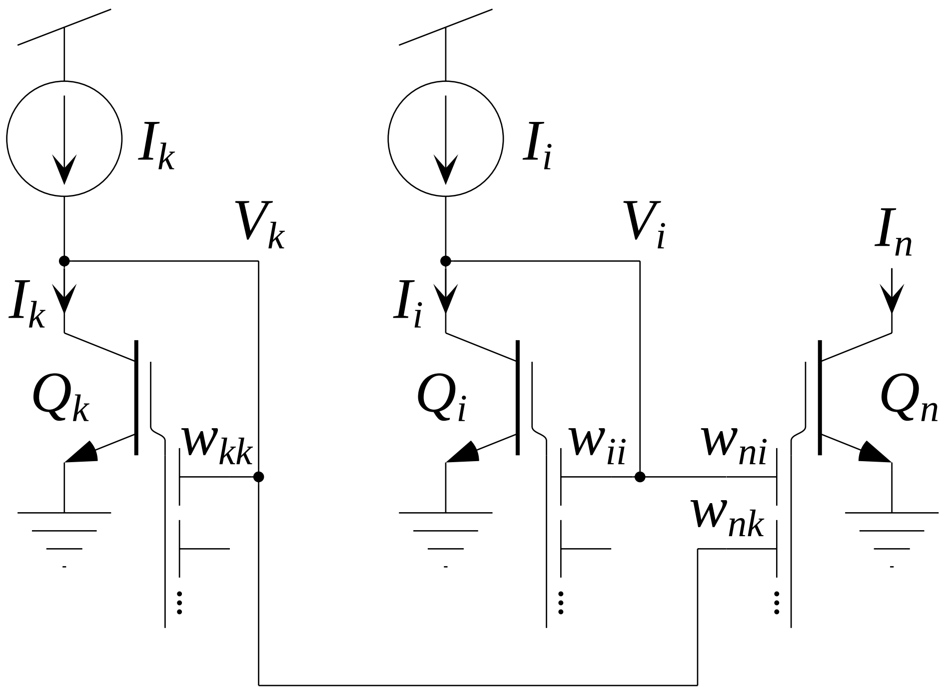
$$I_n \propto \exp\left[\frac{w_{ni} V_i + \ldots}{U_\mathrm{T}}\right]$$

$$\Rightarrow I_n \propto \exp\left[\frac{w_{ni}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{ii}} \log I_i - \ldots\right)\right]$$

$$\Rightarrow I_n \propto \exp\left[\frac{\cancel{U_\mathrm{T}}}{\cancel{U_\mathrm{T}}} \frac{w_{ni}}{w_{ii}} \log I_i\right]$$

$$\Rightarrow \boxed{I_n \propto I_i^{\frac{w_{ni}}{w_{ii}}}}$$

Static MITE Networks: Product-of-Power-Law Circuits



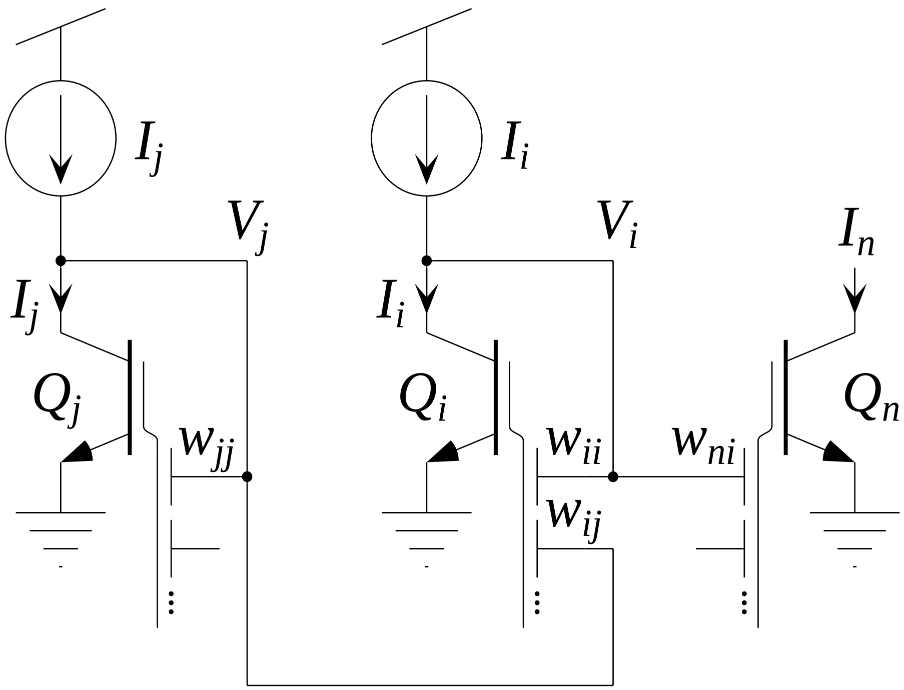
$$I_n \propto \exp\left[\frac{w_{ni}V_i}{U_\mathrm{T}}\right]\exp\left[\frac{w_{nk}V_k}{U_\mathrm{T}}\right]$$

$$\Rightarrow I_n \propto \exp\left[\frac{w_{ni}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{ii}}\log I_i - \ldots\right)\right] \times \exp\left[\frac{w_{nk}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{kk}}\log I_k - \ldots\right)\right]$$

$$\Rightarrow I_n \propto \exp\left[\frac{\cancel{U_\mathrm{T}}}{\cancel{U_\mathrm{T}}}\frac{w_{ni}}{w_{ii}}\log I_i\right] \times \exp\left[\frac{\cancel{U_\mathrm{T}}}{\cancel{U_\mathrm{T}}}\frac{w_{nk}}{w_{kk}}\log I_k\right]$$

$$\Rightarrow \boxed{I_n \propto I_i^{\frac{w_{ni}}{w_{ii}}} \times I_k^{\frac{w_{nk}}{w_{kk}}}}$$

Static MITE Networks: Quotient-of-Power-Law Circuits



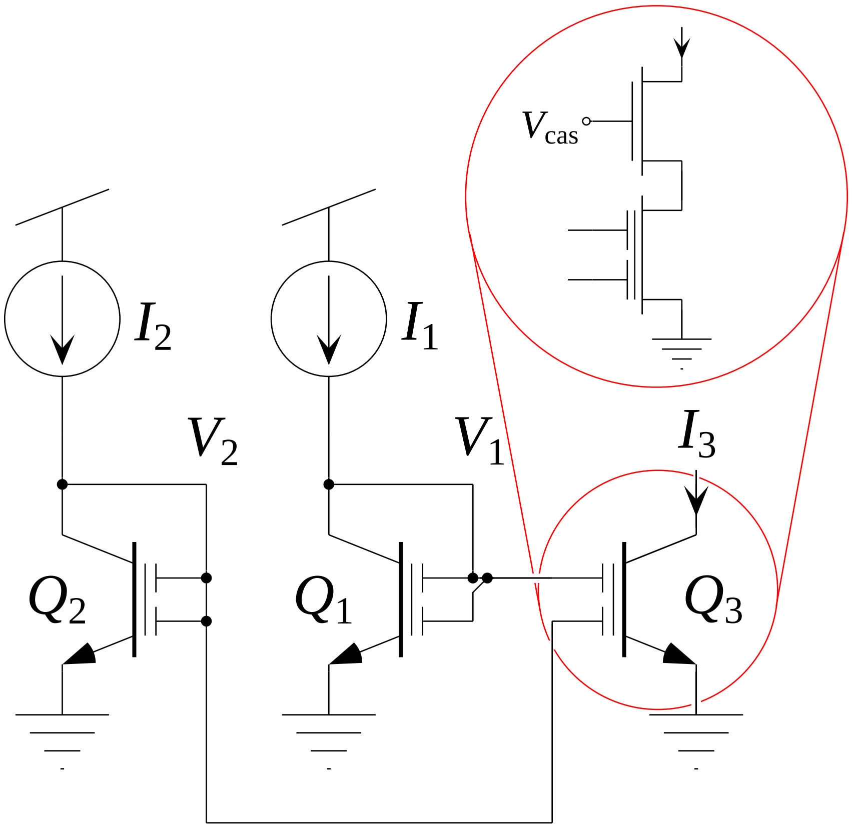
$$I_n \propto \exp\left[\frac{w_{ni}V_i + \ldots}{U_\mathrm{T}}\right]$$

$$\Rightarrow I_n \propto \exp\left[\frac{w_{ni}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{ii}}\log I_i - \frac{w_{ij}}{w_{ii}}\left(\frac{U_\mathrm{T}}{w_{jj}}\log I_j - \ldots\right)\ldots\right)\right]$$

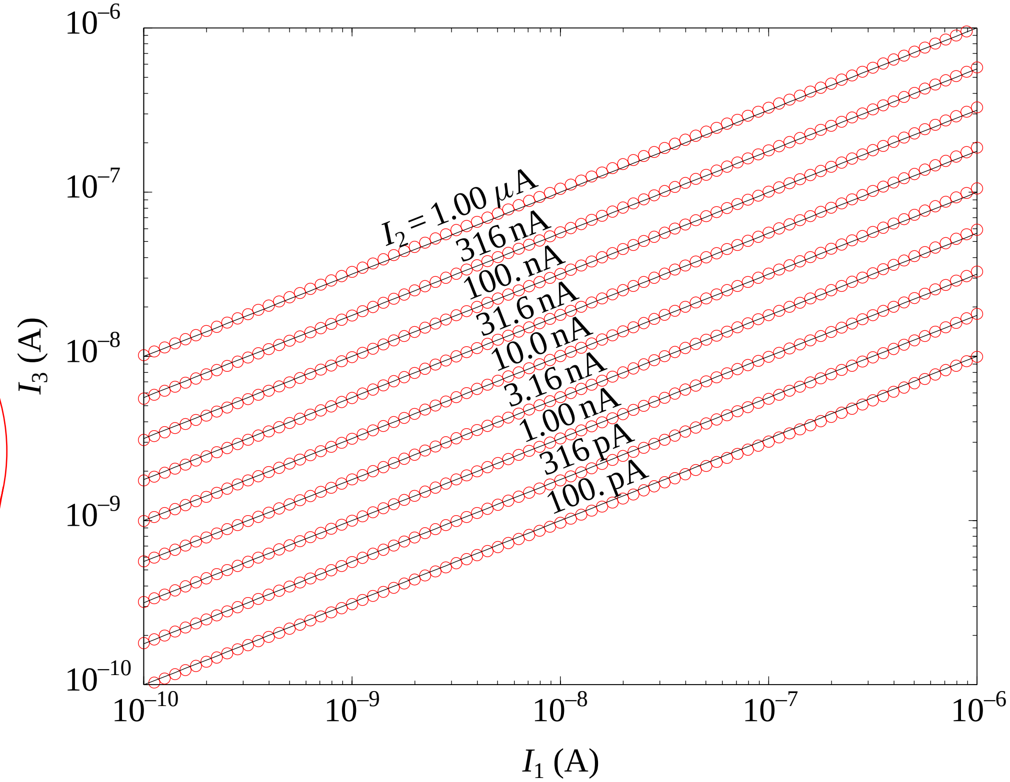
$$\Rightarrow I_n \propto \exp\left[\frac{\cancel{U_\mathrm{T}}}{\cancel{U_\mathrm{T}}}\frac{w_{ni}}{w_{ii}}\log I_i\right] \times \exp\left[-\frac{\cancel{U_\mathrm{T}}}{\cancel{U_\mathrm{T}}}\frac{w_{ni}}{w_{ii}}\frac{w_{ij}}{w_{jj}}\log I_j\right]$$

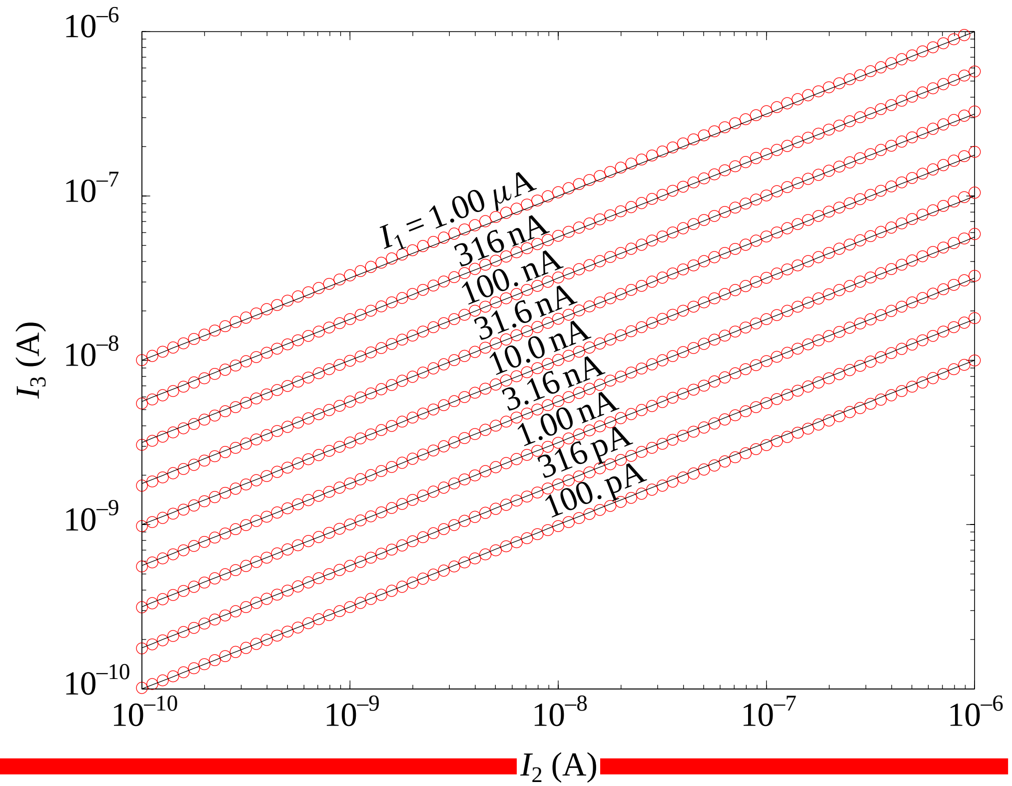
$$\Rightarrow I_n \propto I_i^{\frac{w_{ni}}{w_{ii}}} \times I_j^{-\frac{w_{ni}}{w_{ii}}\frac{w_{ij}}{w_{jj}}} \Rightarrow \boxed{I_n \propto I_i^{\frac{w_{ni}}{w_{ii}}} \div I_j^{\frac{w_{ni}}{w_{ii}}\frac{w_{ij}}{w_{jj}}}}$$

MITE Networks: Geometric Mean



$$I_3 = \sqrt{I_1 I_2}$$





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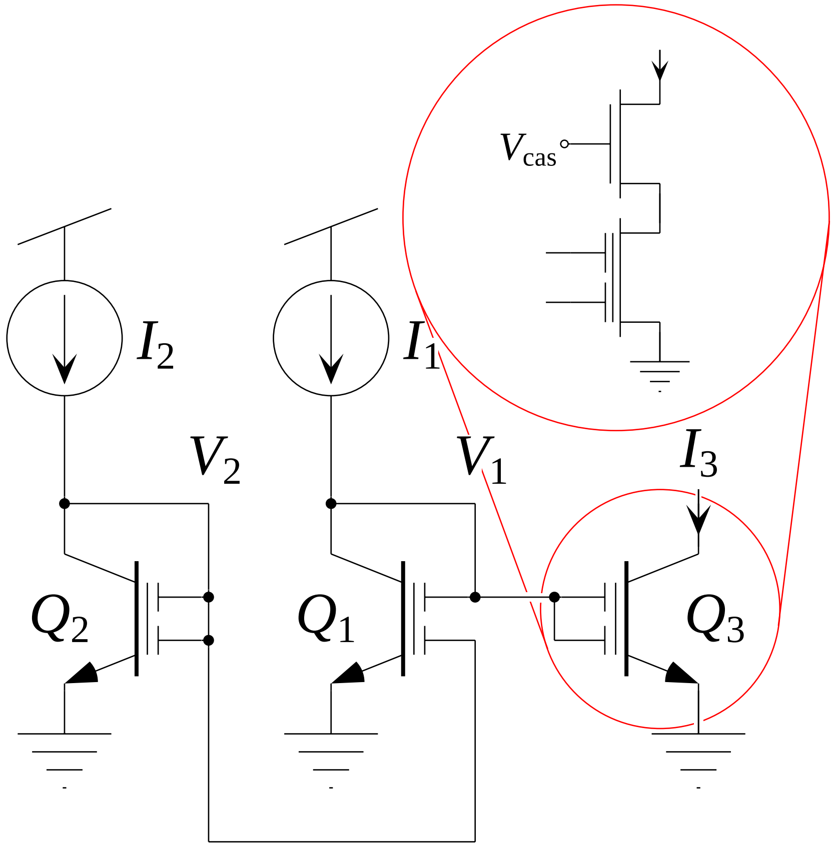
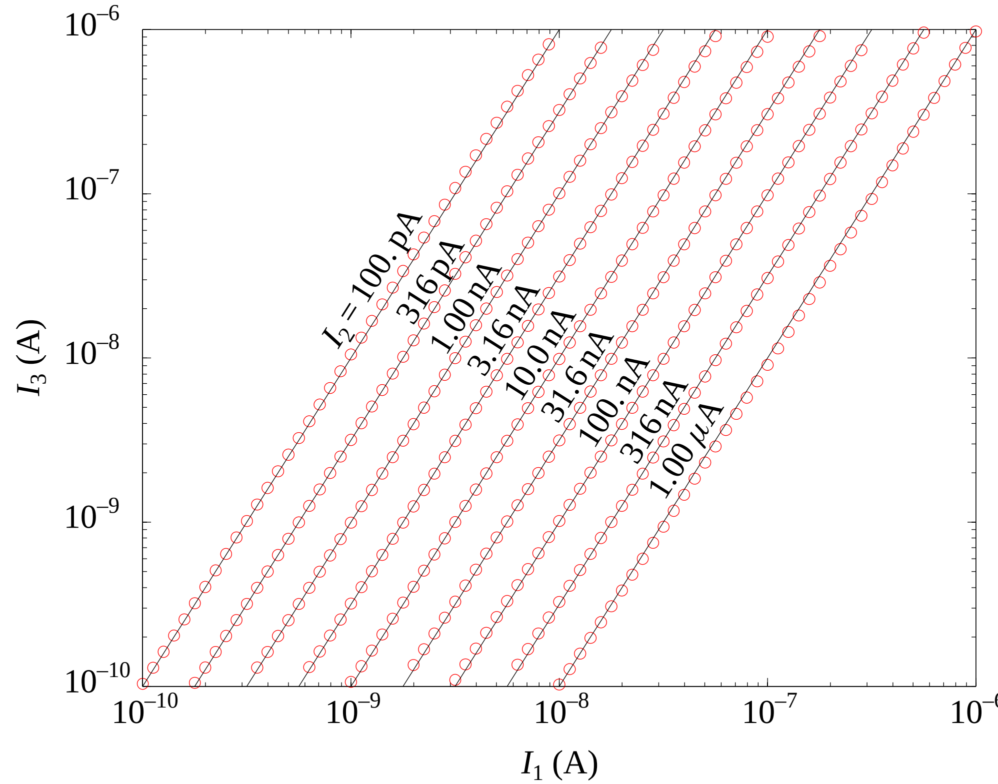
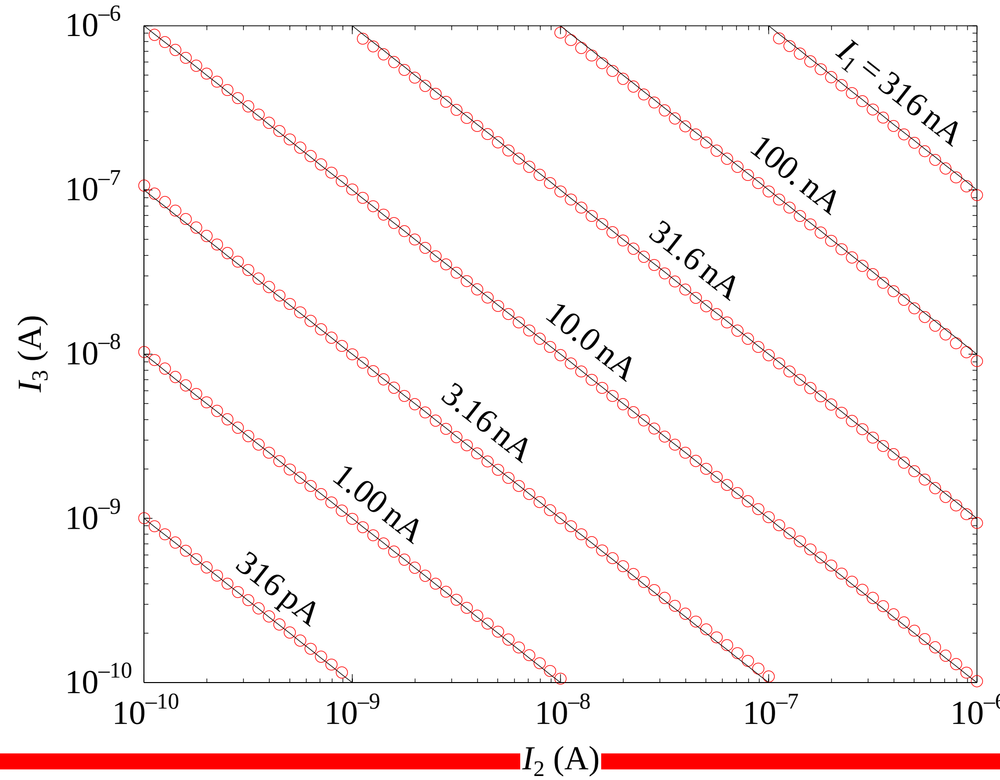
MITE Networks: Square/Reciprocal

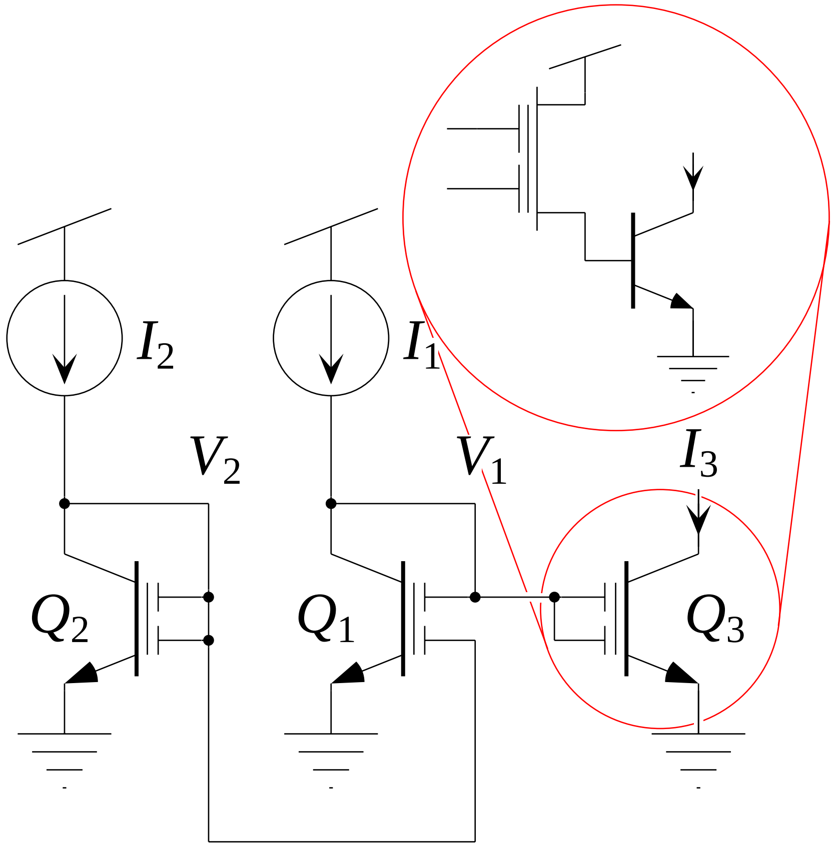


$$\boxed{I_3 = \frac{I_1^{\,2}}{I_2}}$$

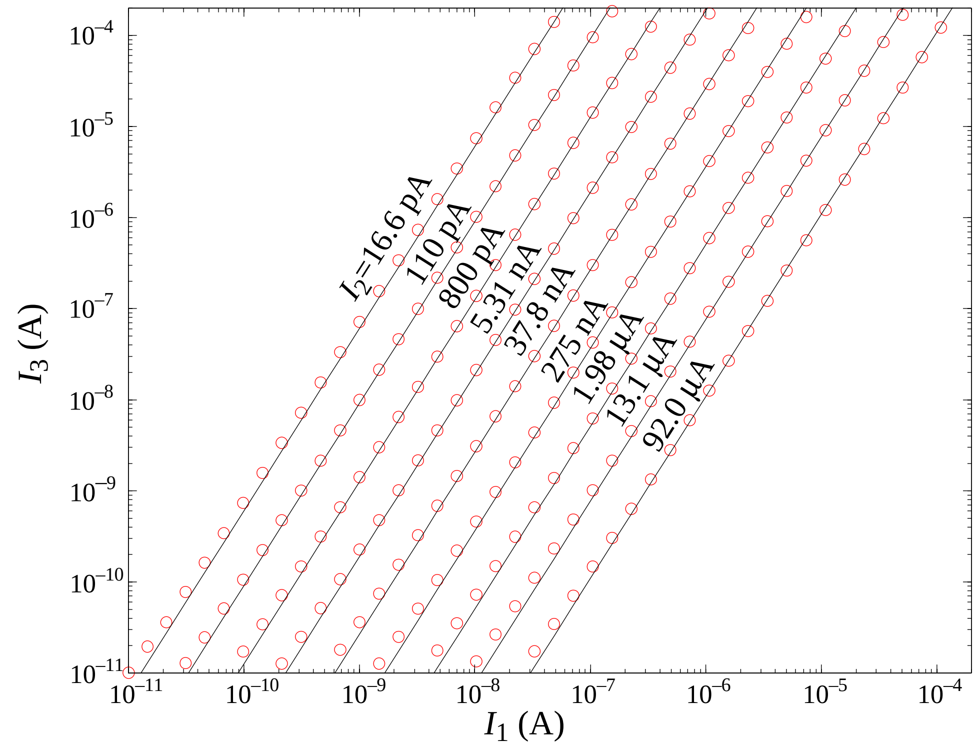


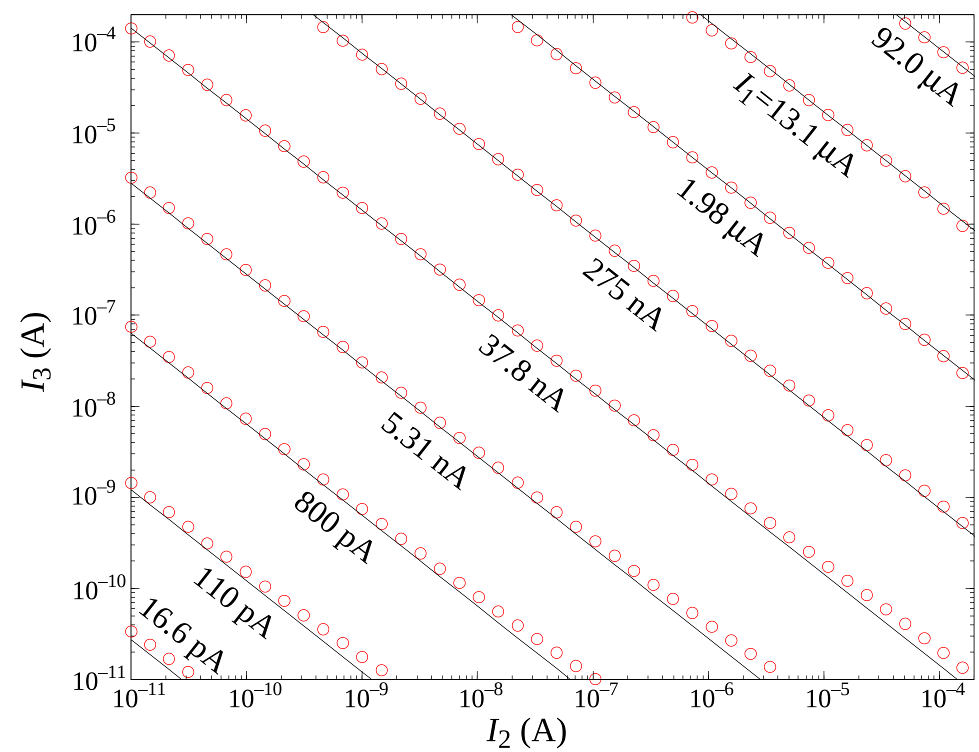


MITE Networks: Square/Reciprocal

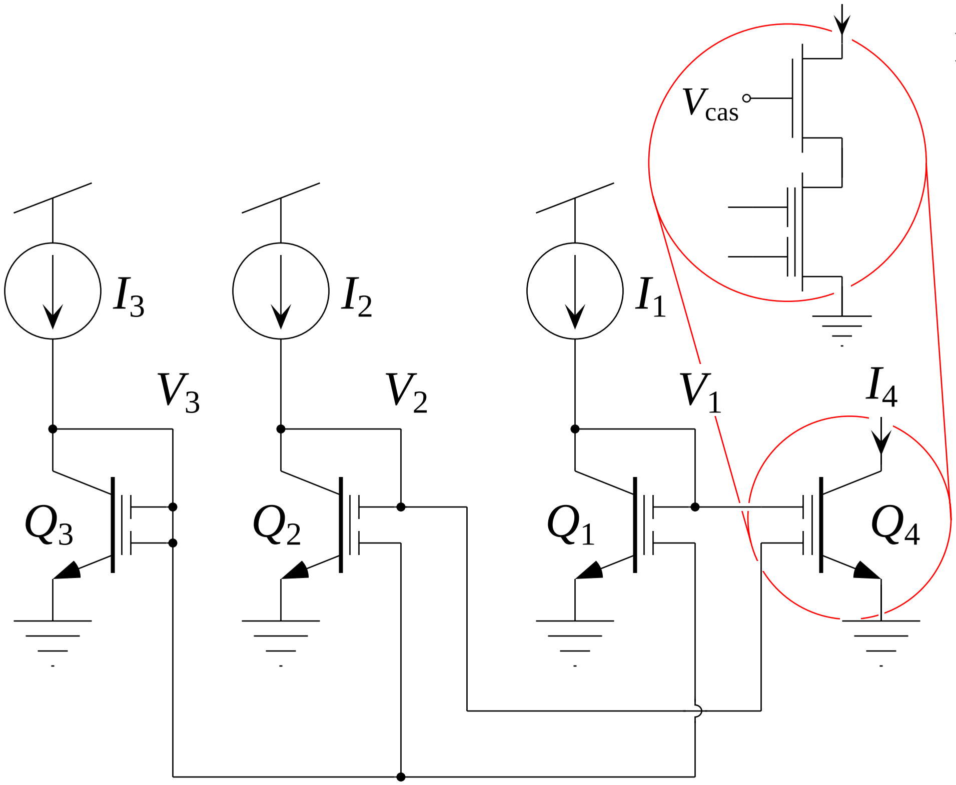


$$\boxed{I_3 = \frac{I_1^{\,2}}{I_2}}$$

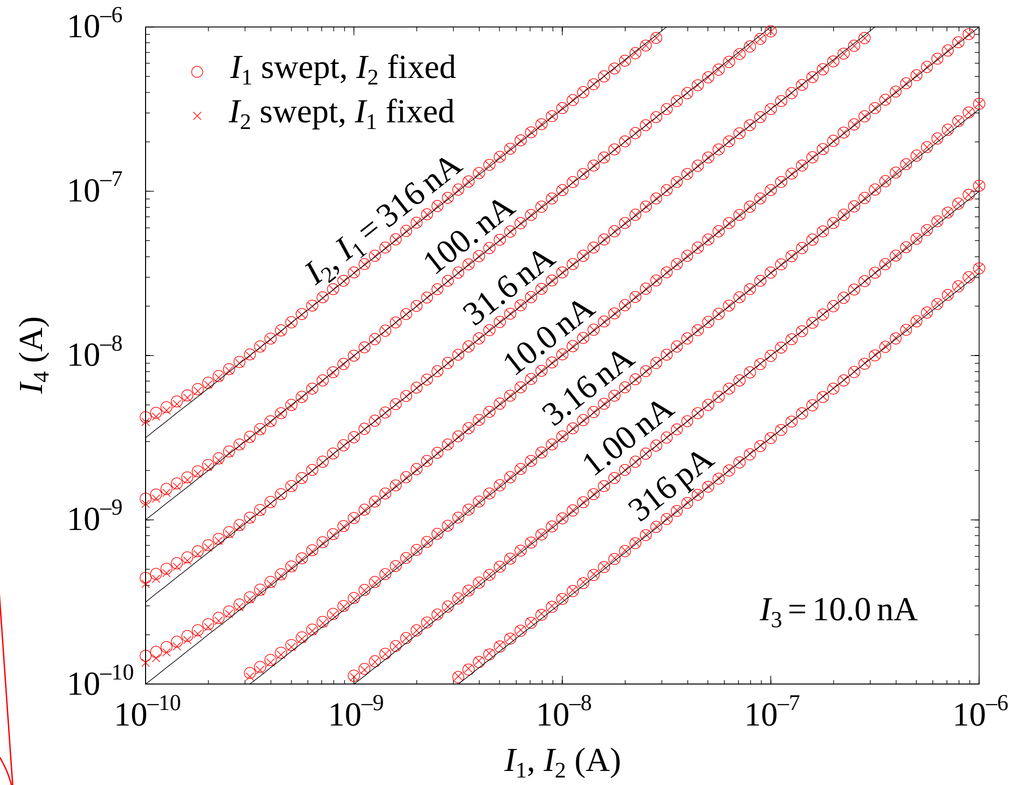


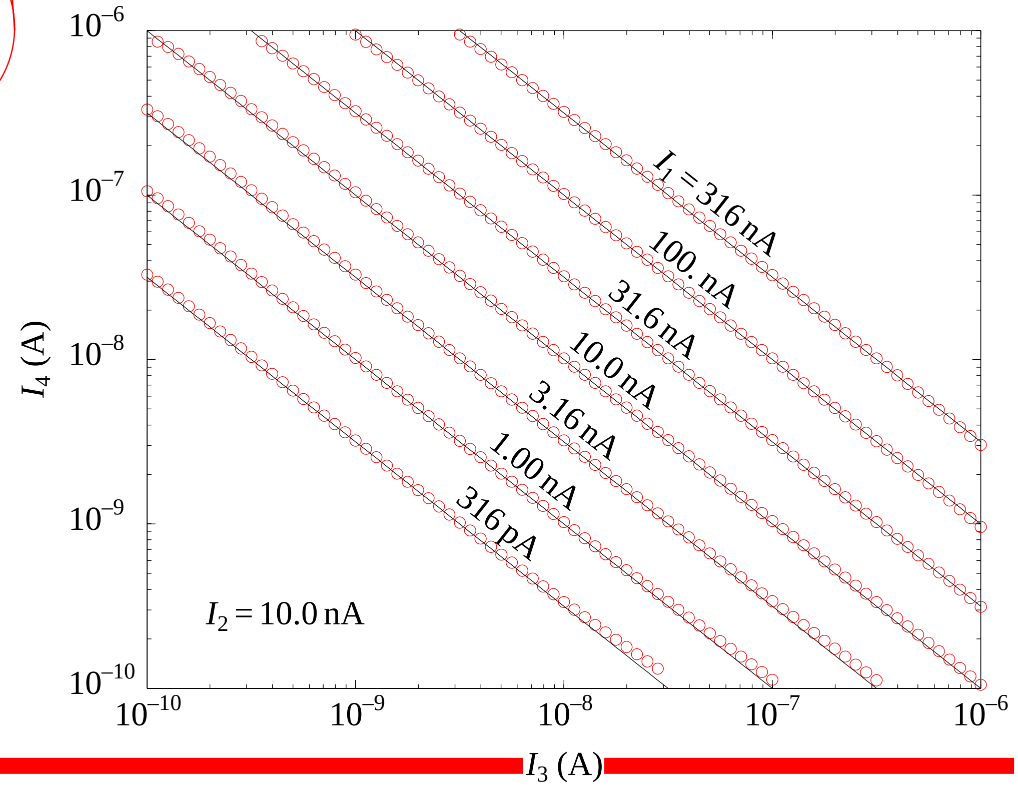


MITE Networks: Multiply/Reciprocal



$$\boxed{I_4 = \frac{I_1 I_2}{I_3}}$$





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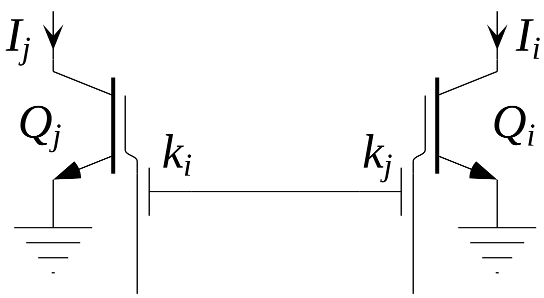
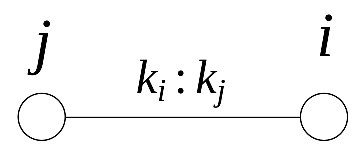
ABC's of MITE Network Synthesis: Acquiring a set of TL Loop Equations

- Begin with a suitable relationship to implement using MITE networks.
- Represent the variables in terms of the ratio of positive signal currents to a unit current, I_u.
- From the original relationship and the signal representations, derive a set of TL loop equations.

ABC's of MITE Network Synthesis: Beginning the Network

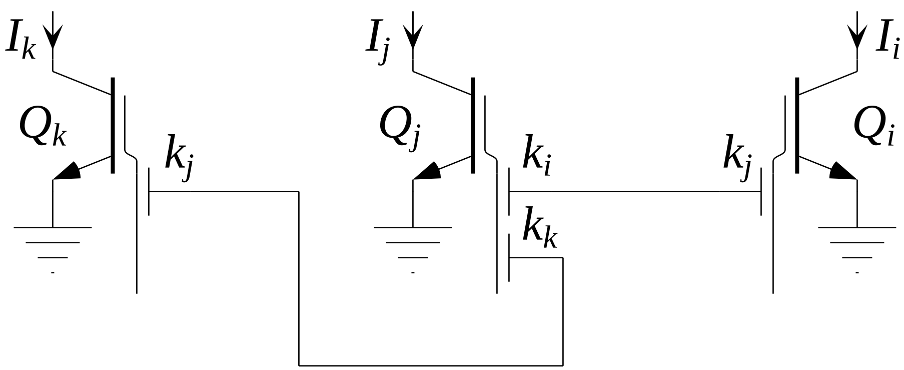
- Begin with a TL loop equation: $\boxed{\displaystyle\prod_{n \in \text{“}CW\text{”}} I_n^{k_n} = \prod_{n \in \text{“}CCW\text{”}} I_n^{k_n}}$
- Pick a current from each set (e.g., I_i from “CW” and I_j from “CCW”), make a new MITE for each, make a new node in the circuit, and couple it into MITE Q_i through k_j unit inputs and into MITE Q_j through k_i unit inputs. If k_i and k_j have a factor in common, they can both be divided by that factor in determining the number of unit inputs.

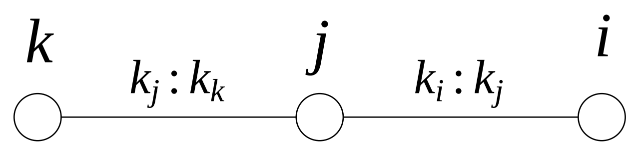




ABC's of MITE Network Synthesis: Building the Network

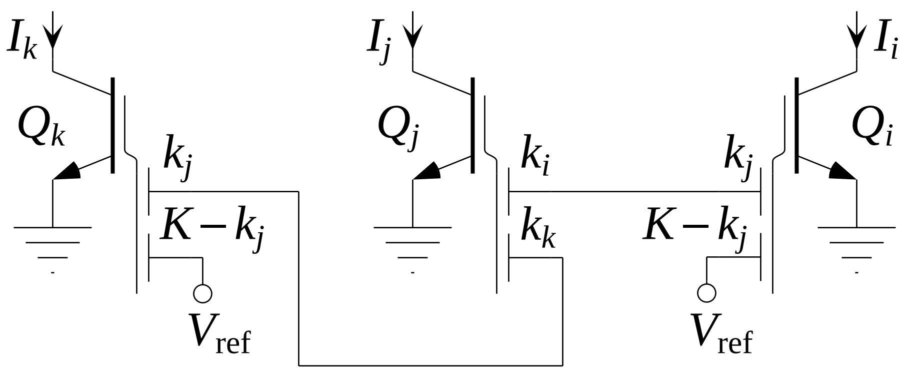
- For each additional current (e.g., I_k from "*CW*"), make a new MITE and connect it to an existing MITE whose current is from the opposite set (e.g., I_j from "*CCW*"), by making a new node and coupling it into MITE Q_k through k_j unit inputs and into MITE Q_j through k_k unit inputs. If k_j and k_k have a factor in common, they can both be divided by that factor in determining the number of unit inputs.

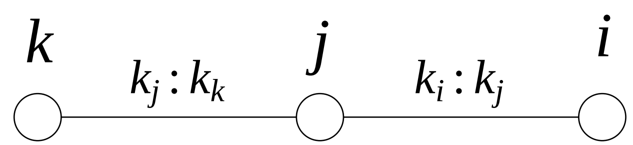




ABC's of MITE Network Synthesis: Balancing the Network

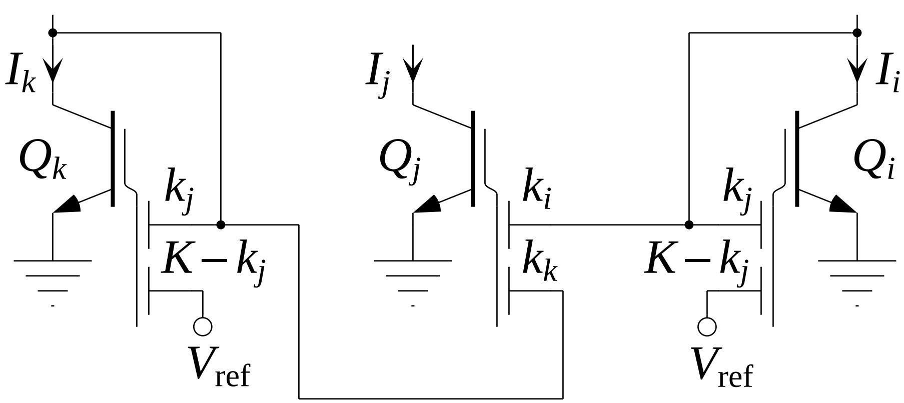
- Suppose that the largest MITE fan-in is K. Add a sufficient number of unit inputs to all MITEs, so they each have a fan-in of K. These unused inputs should be connected to an appropriate voltage so the MITEs operate properly when biased.

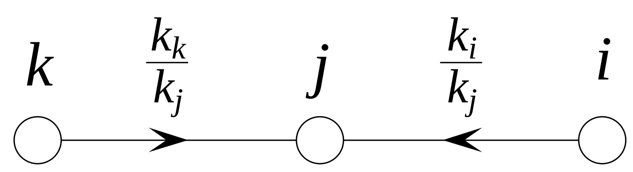




ABC's of MITE Network Synthesis: Biasing the Network

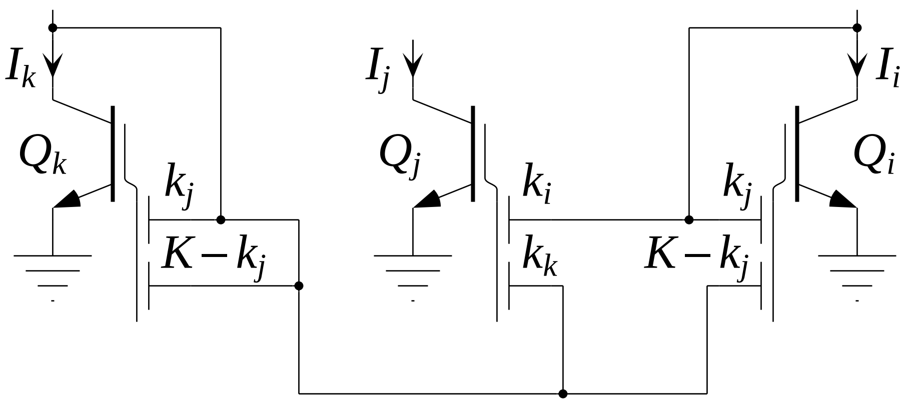
- Bias the MITE network by diode connecting those MITEs whose currents are inputs.

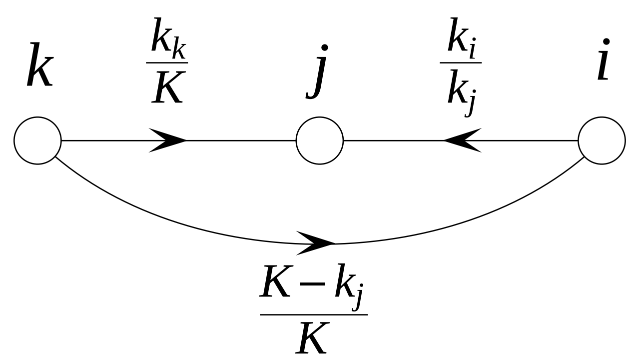




ABC's of MITE Network Synthesis: Completing the Network

- Complete the MITE network by connecting all of the unused inputs to the collector of one of the diode-connected MITEs, avoiding the creation of feedback loops.



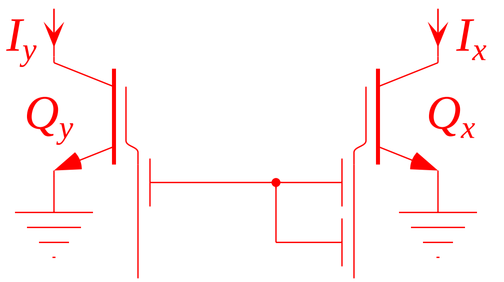


MITE Network Synthesis: Acquiring a TL Equation

$$x = y^2 \quad \Rightarrow \quad \left(\frac{I_x}{I_\mathrm{u}}\right) = \left(\frac{I_y}{I_\mathrm{u}}\right)^2 \quad \Rightarrow \quad \underbrace{I_x I_\mathrm{u}}_{\text{“CW”}} = \underbrace{I_y^2}_{\text{“CCW”}}$$

MITE Network Synthesis: Beginning the Network

$$x = y^2 \quad \Rightarrow \quad \left(\frac{I_x}{I_u}\right) = \left(\frac{I_y}{I_u}\right)^2 \quad \Rightarrow \quad \underbrace{I_x I_u}_{\text{“CW”}} = \underbrace{I_y^2}_{\text{“CCW”}}$$



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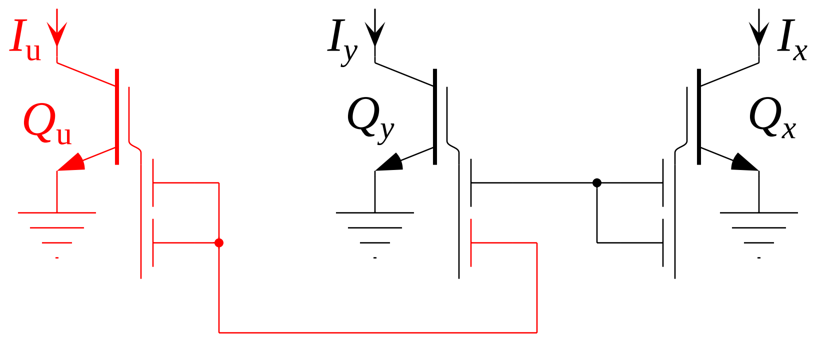
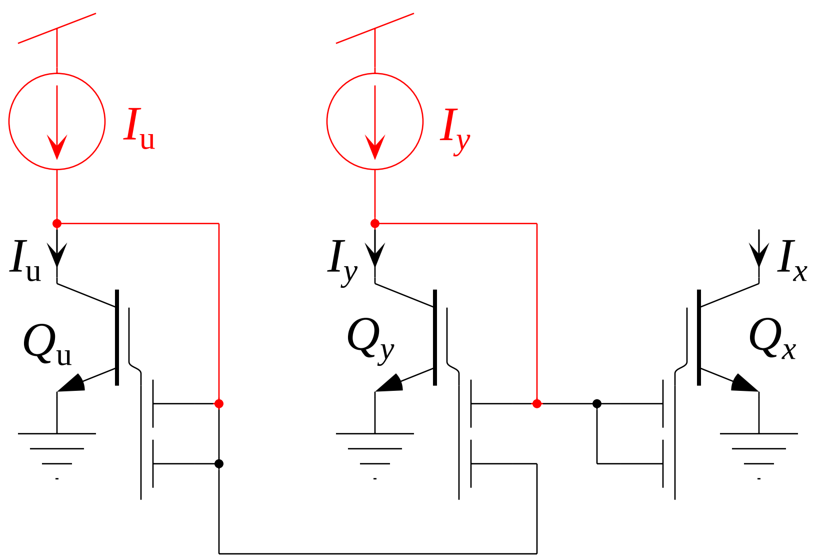
MITE Network Synthesis: Building the Network

$$x = y^2 \quad \Rightarrow \quad \left(\frac{I_x}{I_u}\right) = \left(\frac{I_y}{I_u}\right)^2 \quad \Rightarrow \quad \underbrace{I_x I_u}_{\text{“CW”}} = \underbrace{I_y^2}_{\text{“CCW”}}$$



MITE Network Synthesis: Biasing the Network

$$x = y^2 \quad \Rightarrow \quad \left(\frac{I_x}{I_u}\right) = \left(\frac{I_y}{I_u}\right)^2 \quad \Rightarrow \quad \boxed{I_x = \frac{I_y^2}{I_u}}$$



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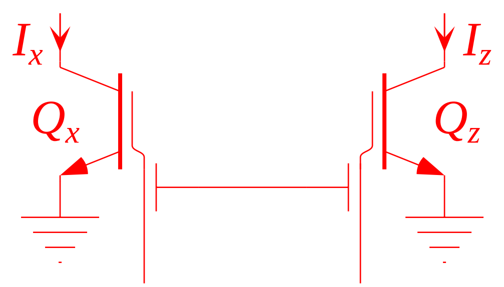
MITE Network Synthesis: Acquiring a TL Equation

$$z = xy \;\Rightarrow\; \left(\frac{I_z}{I_\mathrm{u}}\right) = \left(\frac{I_x}{I_\mathrm{u}}\right)\left(\frac{I_y}{I_\mathrm{u}}\right) \;\Rightarrow\; \underbrace{I_z I_\mathrm{u}}_{\text{“CW”}} = \underbrace{I_x I_y}_{\text{“CCW”}}$$

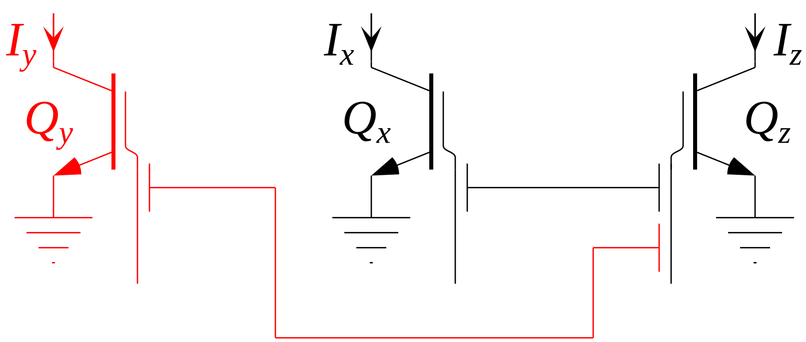
MITE Network Synthesis: Beginning the Network

$$z = xy \;\Rightarrow\; \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \;\Rightarrow\; \underbrace{I_z I_u}_{\text{“CW”}} = \underbrace{I_x I_y}_{\text{“CCW”}}$$



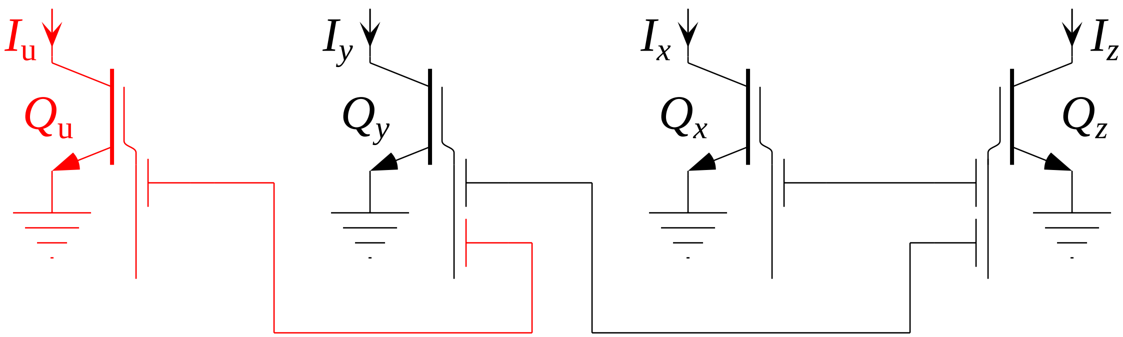
MITE Network Synthesis: Building the Network

$$z = xy \;\Rightarrow\; \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \;\Rightarrow\; \underbrace{I_z I_u}_{\text{“CW”}} = \underbrace{I_x I_y}_{\text{“CCW”}}$$



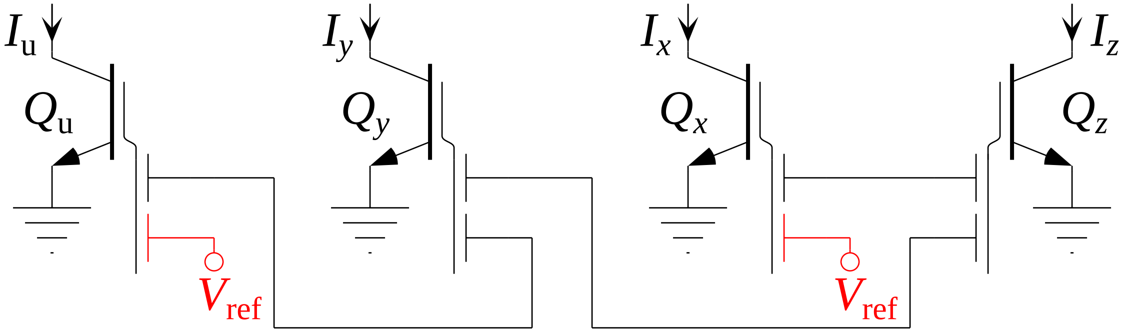
MITE Network Synthesis: Building the Network

$$z = xy \Rightarrow \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \Rightarrow \underbrace{I_z I_u}_{\text{“CW”}} = \underbrace{I_x I_y}_{\text{“CCW”}}$$



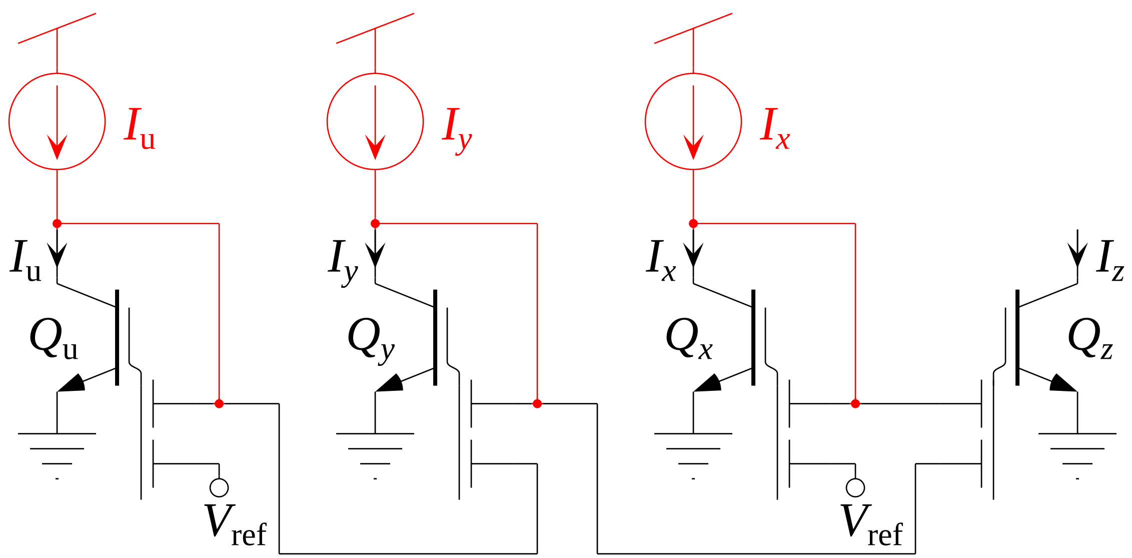
MITE Network Synthesis: Balancing the Network

$$z = xy \;\Rightarrow\; \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \;\Rightarrow\; \underbrace{I_z I_u}_{\text{“CW”}} = \underbrace{I_x I_y}_{\text{“CCW”}}$$



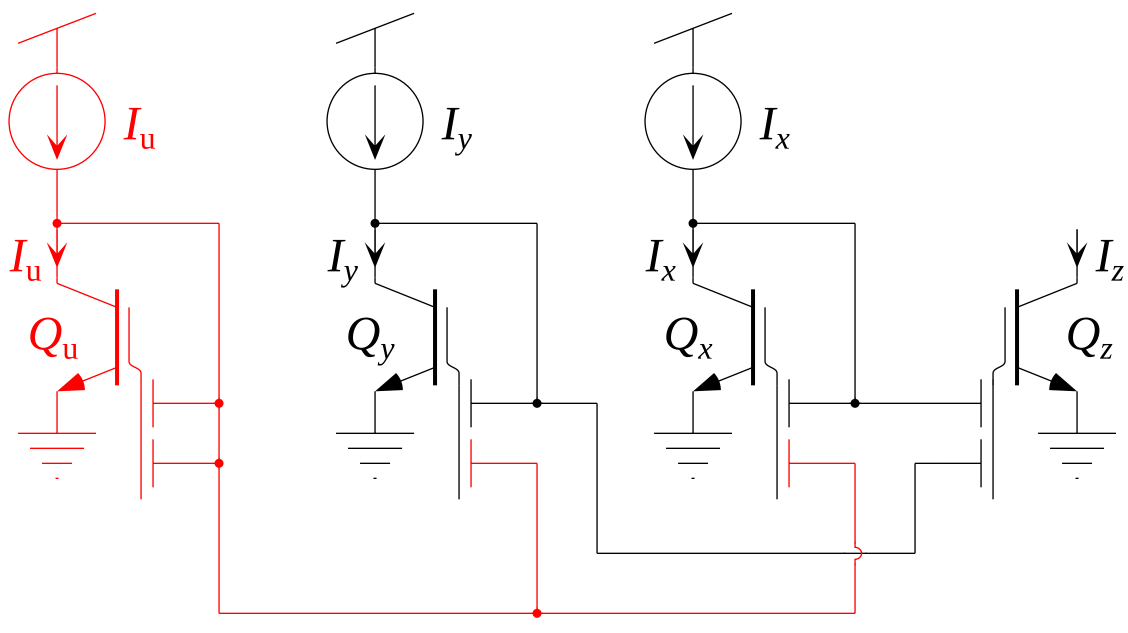
MITE Network Synthesis: Biasing the Network

$$z = xy \;\Rightarrow\; \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \;\Rightarrow\; \boxed{I_z = \frac{I_x I_y}{I_u}}$$



MITE Network Synthesis: Completing the Network

$$z = xy \Rightarrow \left(\frac{I_z}{I_u}\right) = \left(\frac{I_x}{I_u}\right)\left(\frac{I_y}{I_u}\right) \Rightarrow \boxed{I_z = \frac{I_x I_y}{I_u}}$$



MITE Network Synthesis: Vector Magnitude Circuit

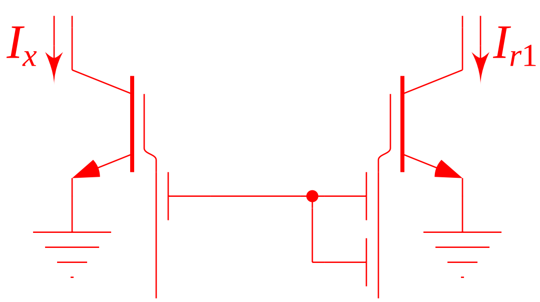
$$r=\sqrt{x^2+y^2} \;\Rightarrow\; \frac{I_r}{I_{\mathrm{u}}}=\sqrt{\left(\frac{I_x}{I_{\mathrm{u}}}\right)^2+\left(\frac{I_y}{I_{\mathrm{u}}}\right)^2} \;\Rightarrow\; I_r^2=I_x^2+I_y^2$$

$$\Rightarrow\; I_r=\underbrace{\frac{I_x^2}{I_r}}_{I_{r1}}+\underbrace{\frac{I_y^2}{I_r}}_{I_{r2}} \;\Rightarrow\; I_r I_{r1}=I_x^2,\; I_r I_{r2}=I_y^2,\; \text{and } I_r=I_{r1}+I_{r2}$$

MITE Network Synthesis: Vector Magnitude Circuit

$$r = \sqrt{x^2 + y^2} \;\Rightarrow\; \frac{I_r}{I_u} = \sqrt{\left(\frac{I_x}{I_u}\right)^2 + \left(\frac{I_y}{I_u}\right)^2} \;\Rightarrow\; I_r^2 = I_x^2 + I_y^2$$

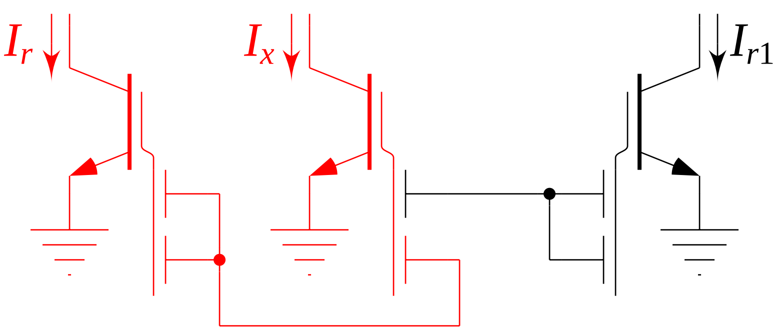
$$\Rightarrow\; I_r = \underbrace{\frac{I_x^2}{I_r}}_{I_{r1}} + \underbrace{\frac{I_y^2}{I_r}}_{I_{r2}} \;\Rightarrow\; I_r I_{r1} = I_x^2,\; I_r I_{r2} = I_y^2,\; \text{and } I_r = I_{r1} + I_{r2}$$



MITE Network Synthesis: Vector Magnitude Circuit

$$r = \sqrt{x^2 + y^2} \quad \Rightarrow \quad \frac{I_r}{I_u} = \sqrt{\left(\frac{I_x}{I_u}\right)^2 + \left(\frac{I_y}{I_u}\right)^2} \quad \Rightarrow \quad I_r^2 = I_x^2 + I_y^2$$

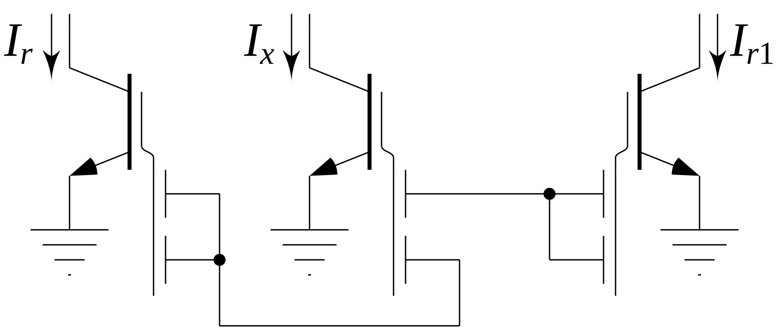
$$\Rightarrow \quad I_r = \underbrace{\frac{I_x^2}{I_r}}_{I_{r1}} + \underbrace{\frac{I_y^2}{I_r}}_{I_{r2}} \quad \Rightarrow \quad I_r I_{r1} = I_x^2,\ I_r I_{r2} = I_y^2,\ \text{and } I_r = I_{r1} + I_{r2}$$

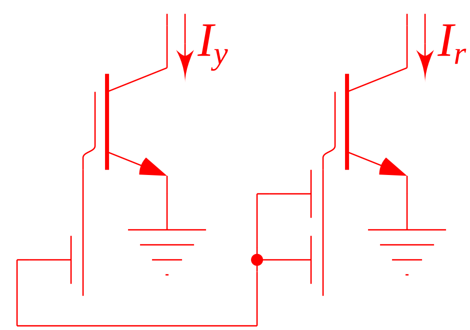


MITE Network Synthesis: Vector Magnitude Circuit

$$r=\sqrt{x^2+y^2} \Rightarrow \frac{I_r}{I_\mathrm{u}}=\sqrt{\left(\frac{I_x}{I_\mathrm{u}}\right)^2+\left(\frac{I_y}{I_\mathrm{u}}\right)^2} \Rightarrow I_r^2=I_x^2+I_y^2$$

$$\Rightarrow I_r=\underbrace{\frac{I_x^2}{I_r}}_{I_{r1}}+\underbrace{\frac{I_y^2}{I_r}}_{I_{r2}} \Rightarrow I_r I_{r1}=I_x^2,\ I_r I_{r2}=I_y^2,\ \text{and } I_r=I_{r1}+I_{r2}$$





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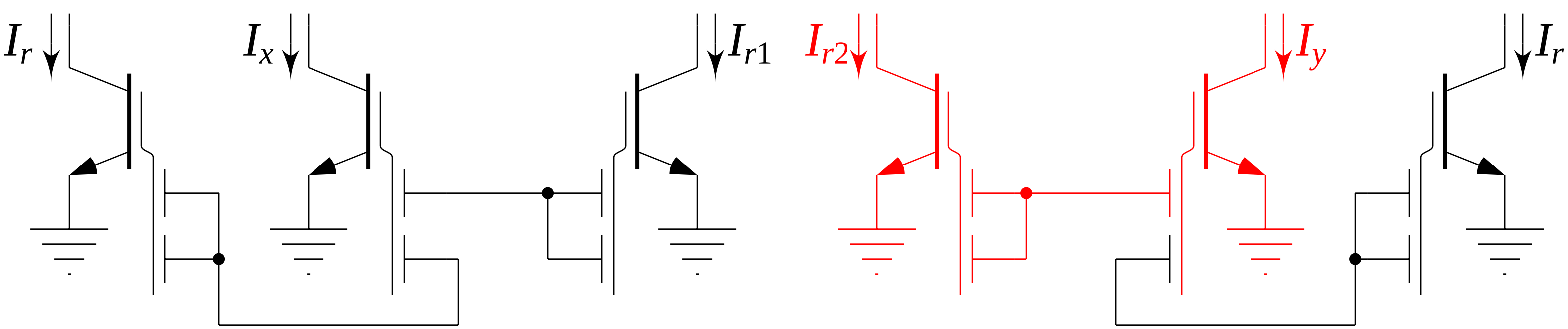

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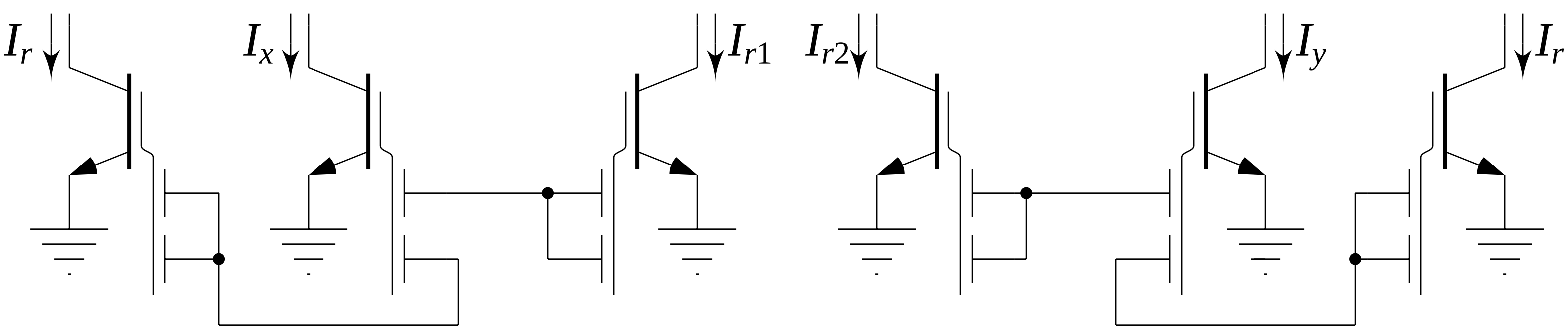

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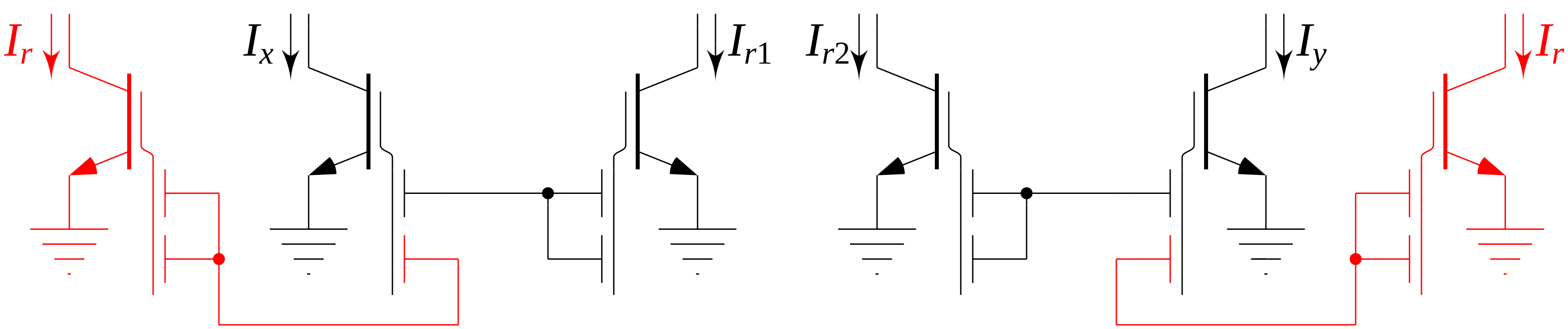

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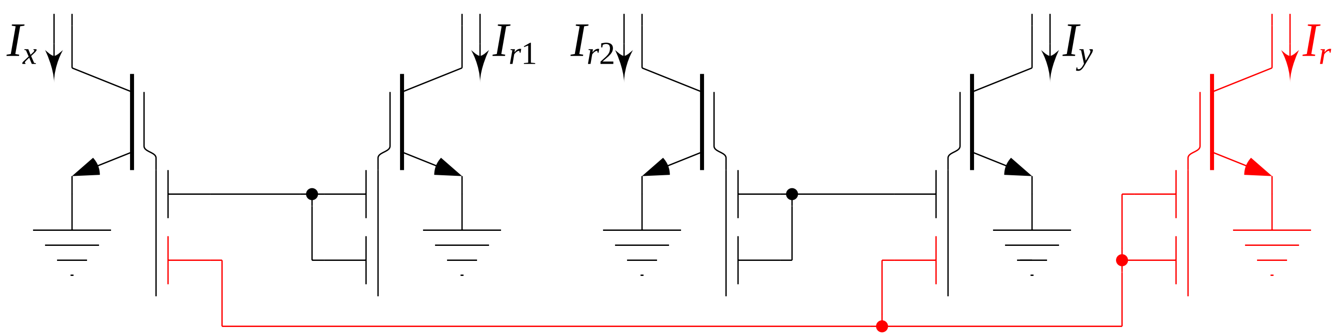

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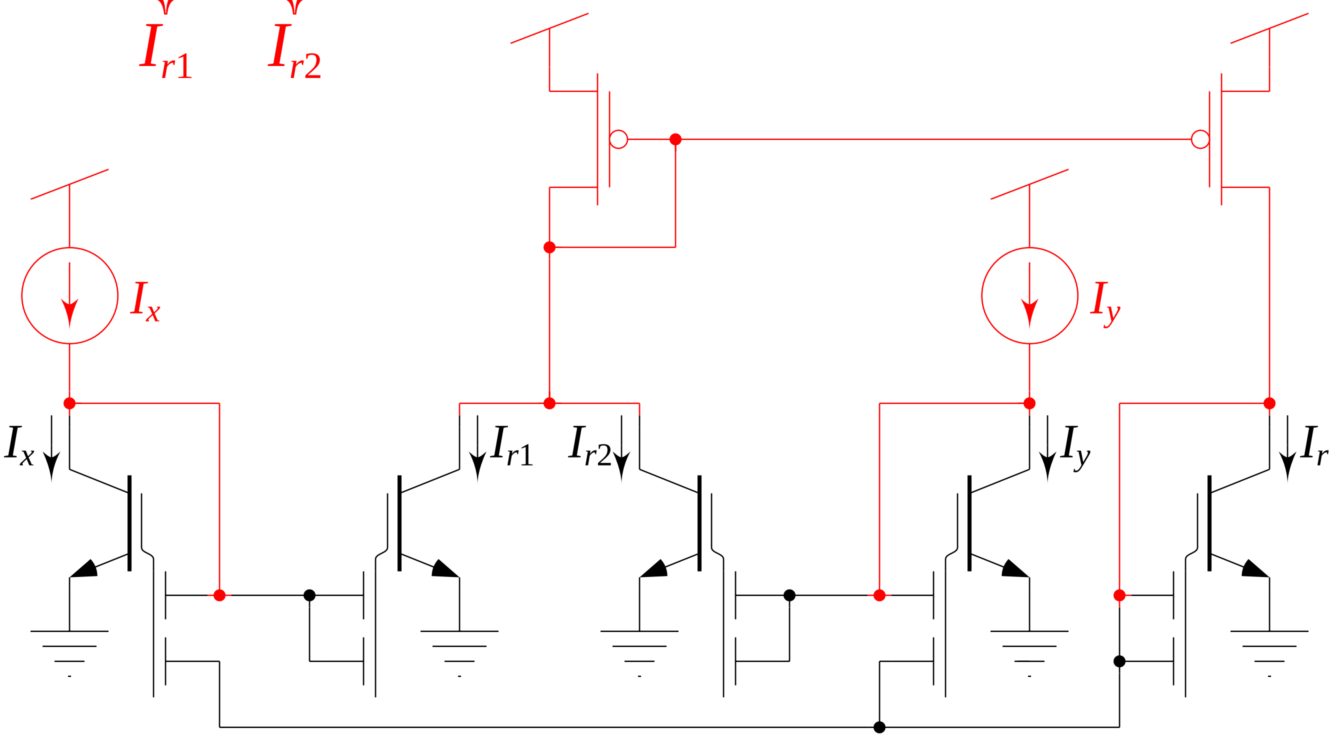

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MITE Network Synthesis: Vector Magnitude Circuit

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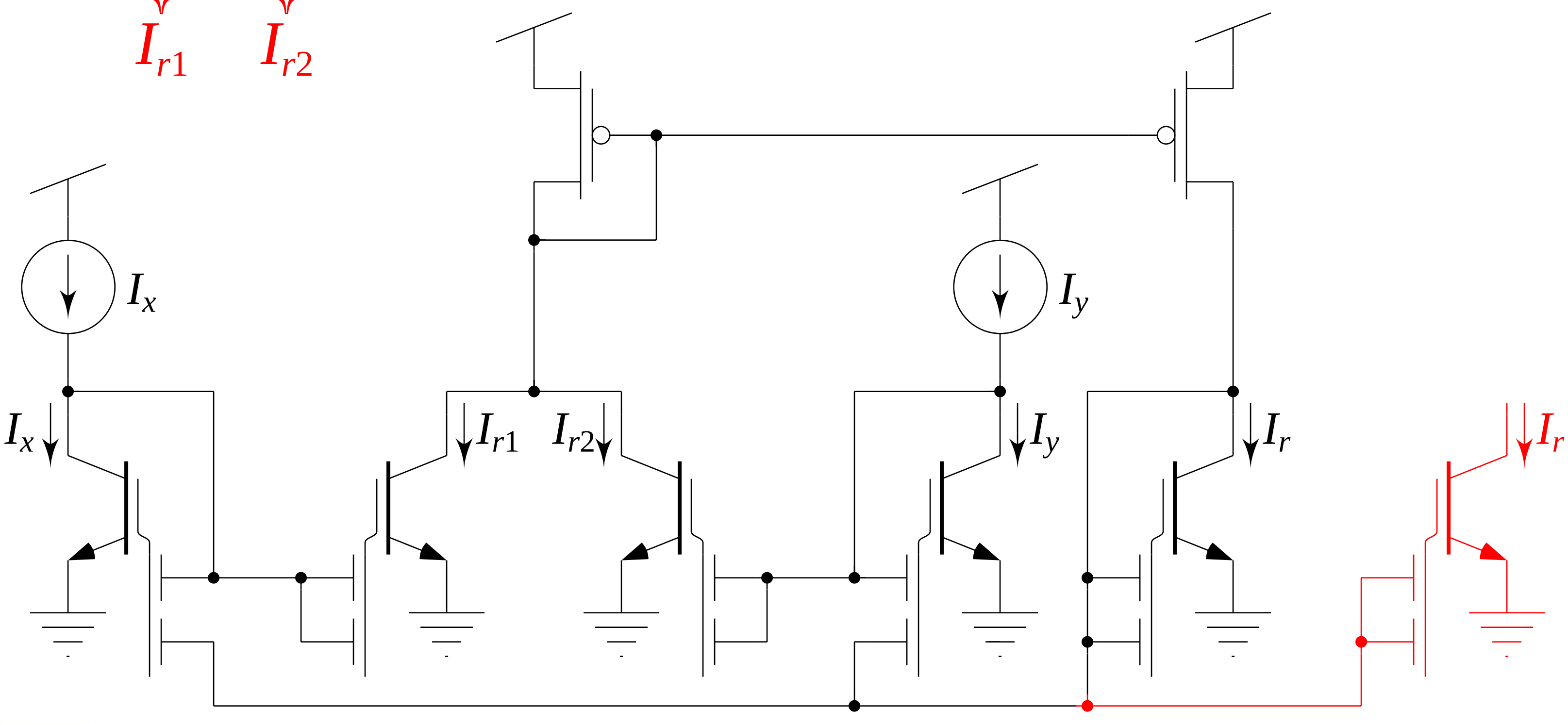

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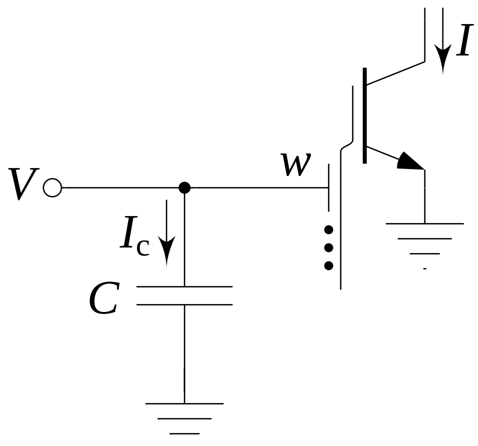
Implementing Dynamic Constraints: Output Structures

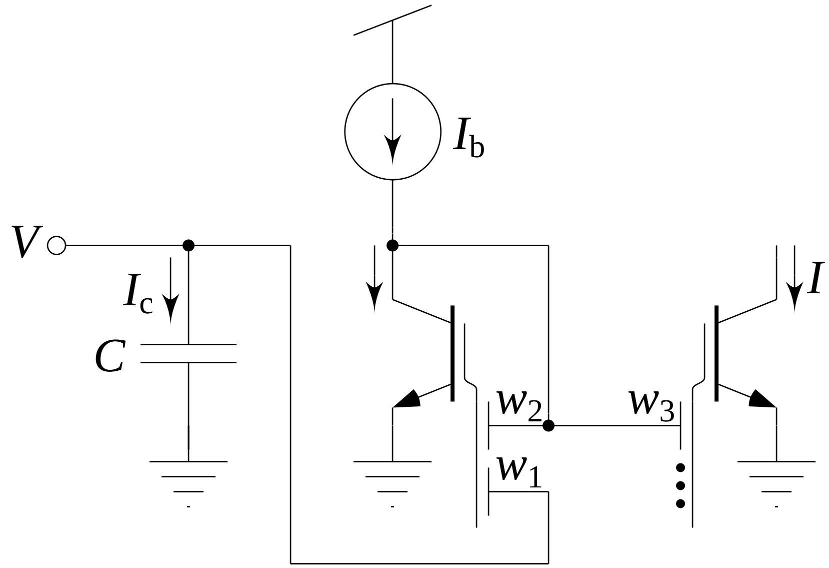
Noninverting



$$I \propto e^{wV/U_T}$$

$$\Rightarrow \boxed{\frac{\partial I}{\partial V} = \frac{wI}{U_T}}$$

Inverting



$$I \propto e^{-wV/U_T}$$

$$\Rightarrow \boxed{\frac{\partial I}{\partial V} = -\frac{wI}{U_T}}$$

$$\text{where } w = \frac{w_1 w_3}{w_2}$$

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Dynamic MITE Network Synthesis: First-Order Lowpass Filter

$$\tau\frac{dy}{dt}+y=x \Rightarrow \tau\frac{d}{dt}\left(\frac{I_y}{I_\mathrm{u}}\right)+\left(\frac{I_y}{I_\mathrm{u}}\right)=\left(\frac{I_x}{I_\mathrm{u}}\right) \Rightarrow \tau\frac{dI_y}{dt}+I_y=I_x$$

$$\Rightarrow \tau\frac{dI_y}{dV}\cdot\frac{dV}{dt}+I_y=I_x \Rightarrow \tau\left(-\frac{wI_y}{U_\mathrm{T}}\right)\frac{dV}{dt}+I_y=I_x \Rightarrow -\underbrace{\frac{w\tau}{U_\mathrm{T}}\cdot\frac{1}{C}}_{1/I_\tau}\cdot\overbrace{C\frac{dV}{dt}}^{I_\mathrm{c}}+1=\frac{I_x}{I_y}$$

$$\Rightarrow -\frac{I_\mathrm{c}}{I_\tau}+1=\frac{I_x}{I_y} \Rightarrow \underbrace{I_\tau-I_\mathrm{c}}_{I_p}=\frac{I_\tau I_x}{I_y} \Rightarrow I_pI_y=I_\tau I_x \text{ and } I_\tau=I_p+I_\mathrm{c}$$

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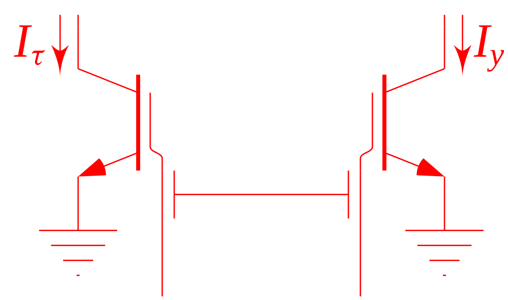
$$\Rightarrow -\frac{w\tau}{\underbrace{U_\mathrm{T}\; C}_{1/I_\tau}}\cdot\frac{\overbrace{C\; dV}^{I_\mathrm{c}}}{dt} + 1 = \frac{I_x}{I_y} \;\Rightarrow\; \underbrace{I_\tau - I_\mathrm{c}}_{I_p} = \frac{I_\tau I_x}{I_y} \;\Rightarrow\; I_p I_y = I_\tau I_x \;\; \text{and} \;\; I_\tau = I_p + I_\mathrm{c}$$



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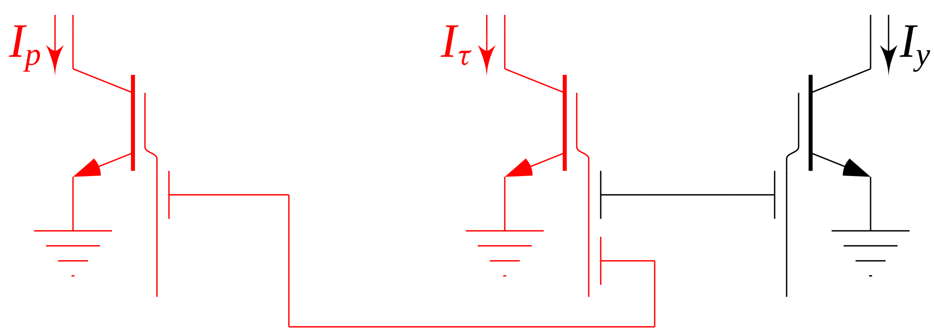

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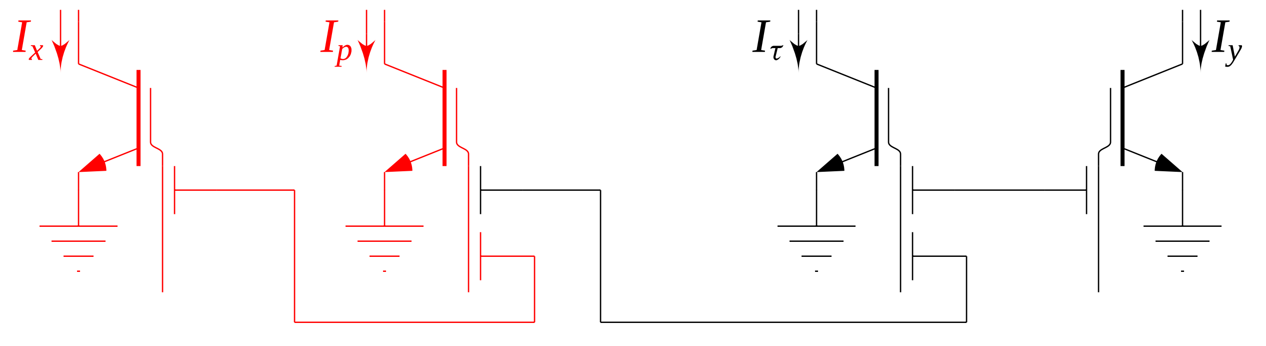

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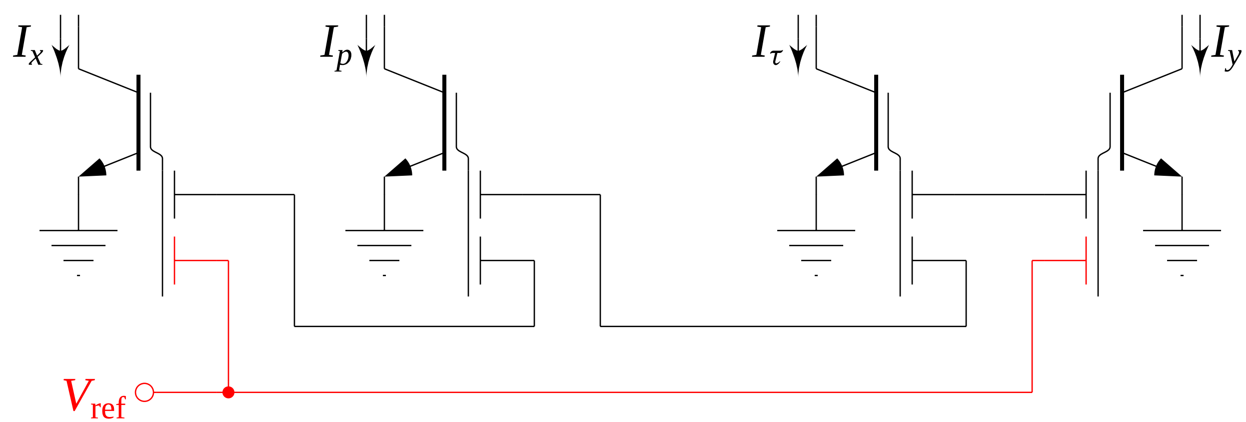

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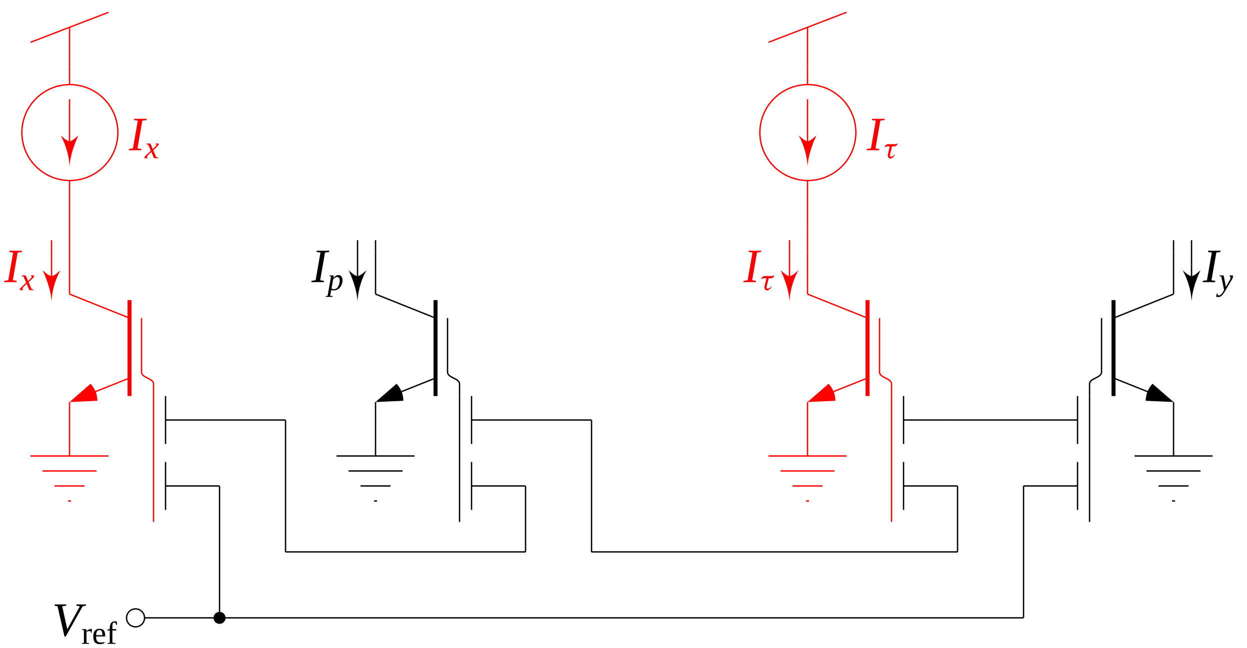

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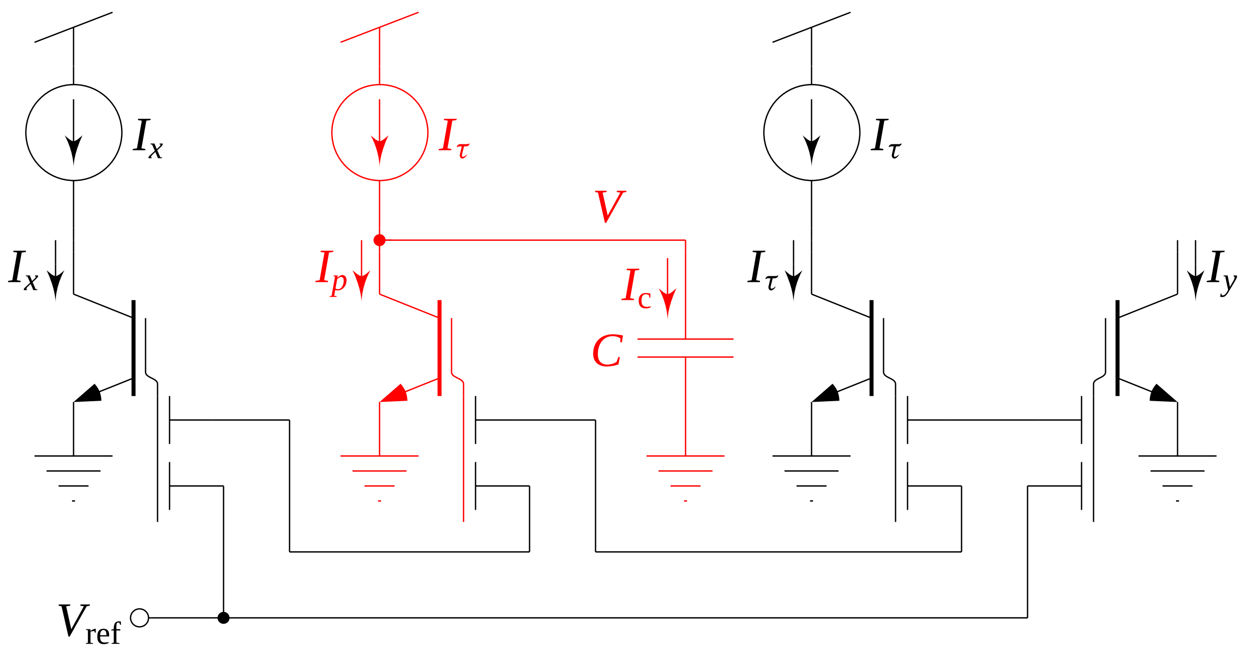

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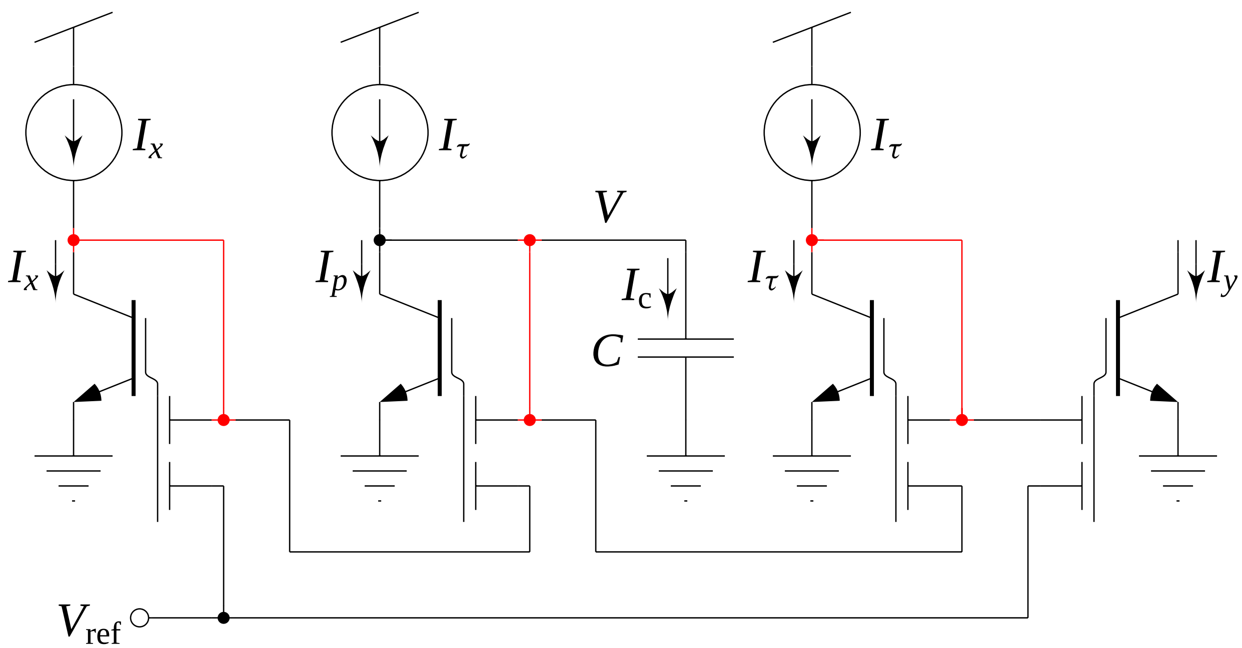

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