Lecture 6

of

EEE307

Electronics for Communications

Department of Electrical & **Electronic Engineering**

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 18th October 2019

- Fibre-Optic Communications
- Trans-Impedance Amplifier (TIA)
  - one of the four amplifier types
  - from inverting amplifier
- Common-gate configuration as TIA
  - current amplification

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Fibre-Optic Communications

(data transmission above 10 Gbps)

- With the increasing demand for high speed data transmission, **fibre-optic communications** have important applications not only in long distance communications but also in situations such as data centres which store and process the immensely increasing amount of digital data (e.g. from social media).

Image taken from website of Finisar Corporation; available at: https://www.finisar.com/markets/data-center.

- The typical data transmission rate is well above 10 **gigabit per second** (**Gbps**), up to 120 Gbps.

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Fibre-Optic Communications

(optical signals over fibre-optical cable)

- The high speed data transmission is achieved by sending and receiving optical signals over a fibre-optic cable.

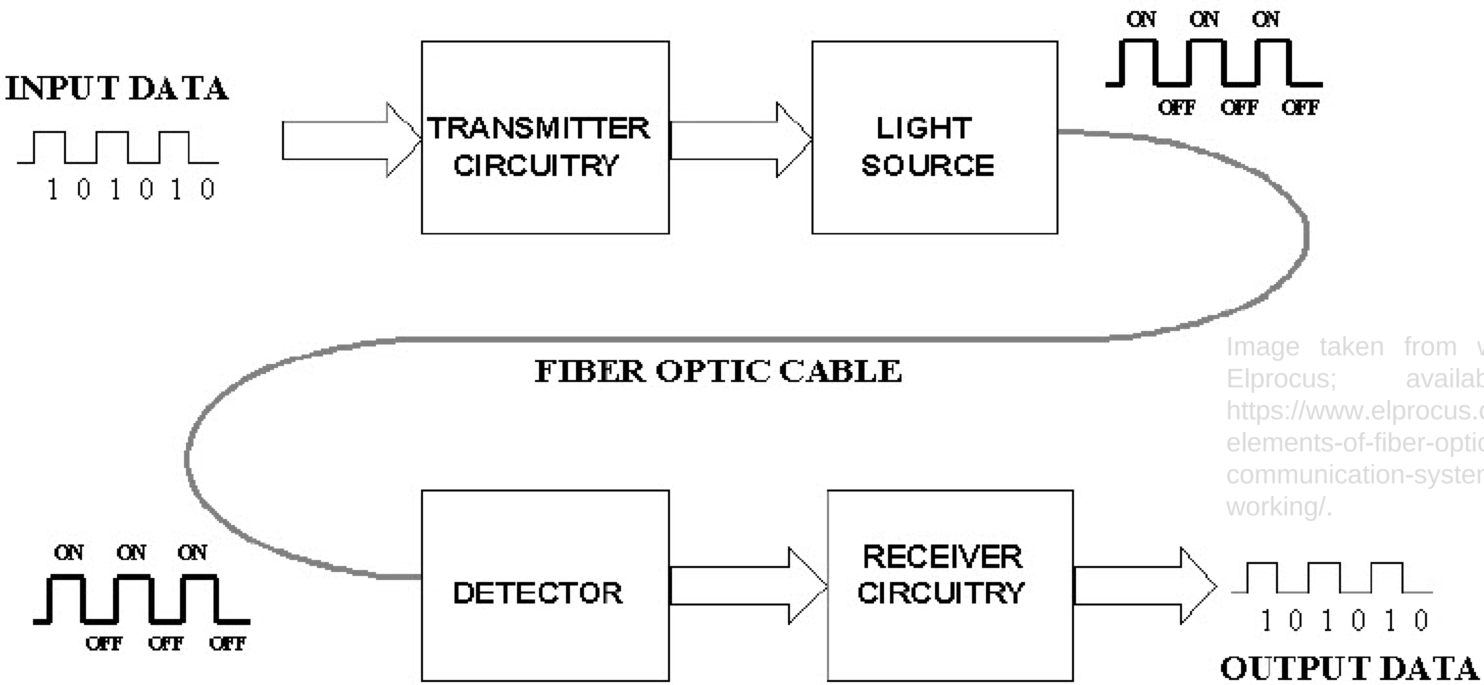


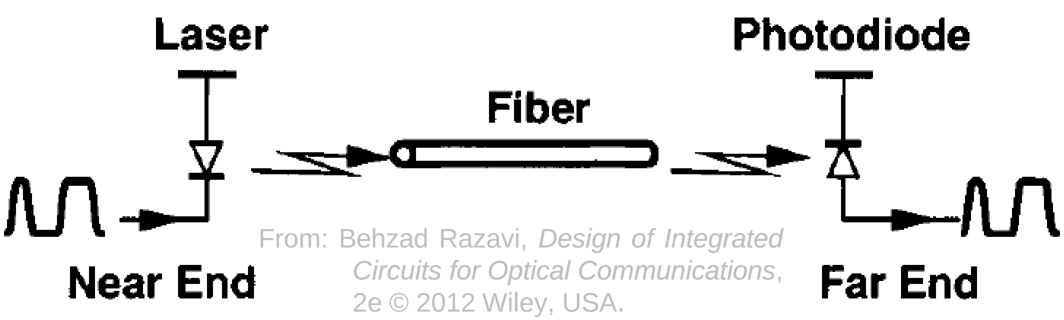
Image taken from website of Elprocus; available at: https://www.elprocus.com/basic-elements-of-fiber-optic-communication-system-and-its-working/.

  - a light source & a detector at both ends of the fiber-optic cable.

Fibre-Optic Communications

(data transmission above Gbs)

- ❑ In such fibre-optic communication systems for high-speed data transmission, a light source needs to be switched on and off at frequencies above GHz; at the same time the optical detector needs to respond fast enough to the optical signals transmitted over the optical fibre.
  - A semiconductor **laser diode** (LD) and **photodiode** can respectively serve for such purposes.



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

  - A semiconductor **light-emitting diode** (**LED**) would also work, but with lower speed of data transmission.
  - The **spectral purity** of LEDs is worse than LD.
  - Related photonics is taught in EEE314.

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Fibre-Optic Communications

(data transmission above Gbs)

- The **laser diode** in such fibre-optic communiation systems is like a ***transmitting*** **antenna**. It converts electrical signals into optical signals to be transmitted over the optical fibre.
  - An electronic circuit is needed to ***drive*** the **laser diode**. This is equivalent to a **power amplifier** to drive the antenna.

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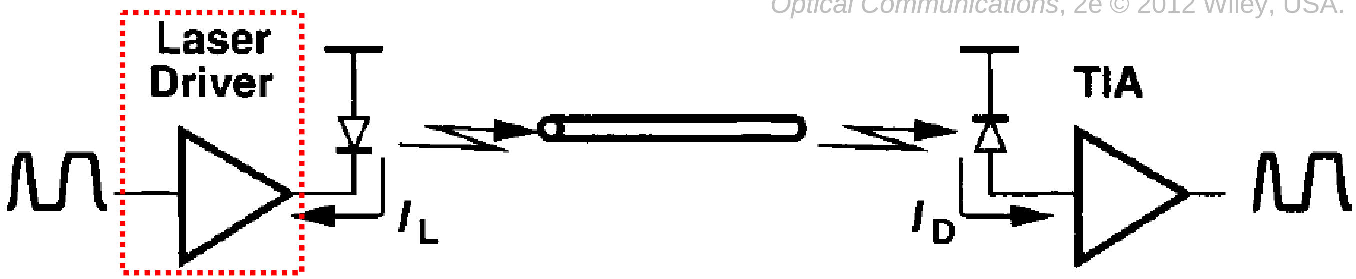

  - The laser driver circuit needs to deliver a fairly large current to the laser diode to produce high enough light intensity (with power of e.g. 10 mW).

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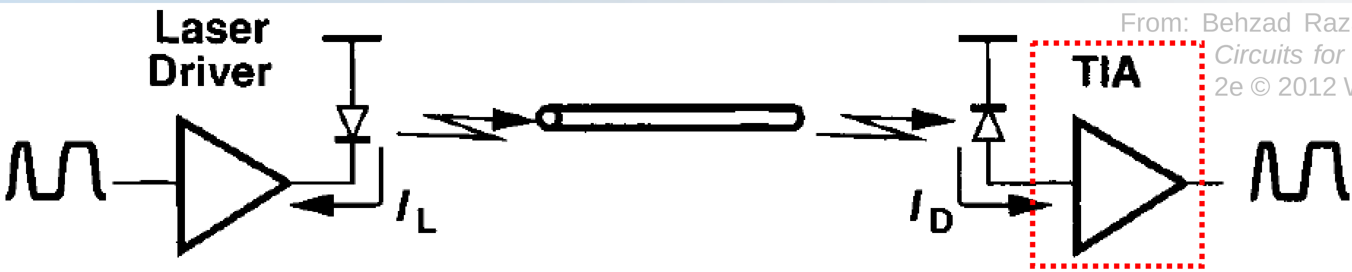
Fibre-Optic Communications

(data transmission above Gbs)



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

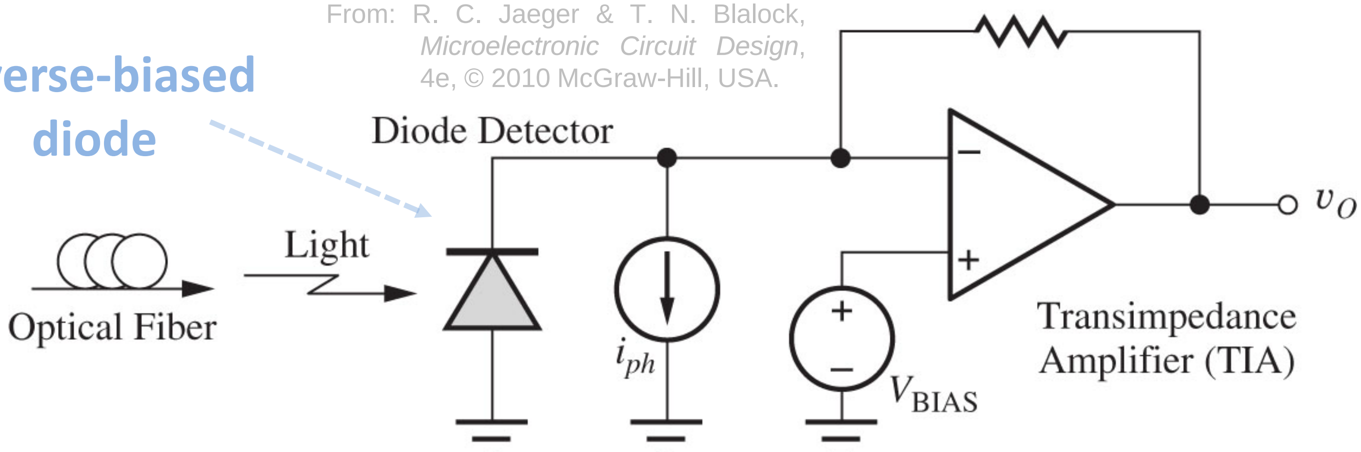
- Similarly, the **photodiode** in such fibre-optic communiation systems is like a ***receiving*** **antenna**. It converts *attenuated* optical signals back to electrical signals.
  - An electronic circuit is needed to ***amplify*** the electrical signals generated by the **photodiode**. This is equivalent to a **low-noise amplifier** (**LNA**) to drive the antenna.
- As the output of the **photodiode** is a weak current signal, a **trans-impedance amplifier** (TIA) is used to amplify the signals to a voltage signal.
  - low noise & large enough bandwidth

Fibre-Optic Communications
(data transmission above Gbs)

- The implementation of such an electronic circuit is not complicated for detecting the optical signals and converting into electric currents and then amplifying to voltage signals.

reverse-biased diode

From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.



- The **trans-impedance amplifier** (**TIA**) can be constructed using an **operational amplifier** (op amp) and a feedback resistor in its simplest case.
  - Note op amp configuration in the **TIA**.

Trans-Impedance Amplifier (TIA)

(4 amplifier types)

- The **trans-impedance amplifier** (**TIA**) is one of four types of amplifiers, depending on whether the amplifier senses a voltage or current at the input and produces a voltage or current output.

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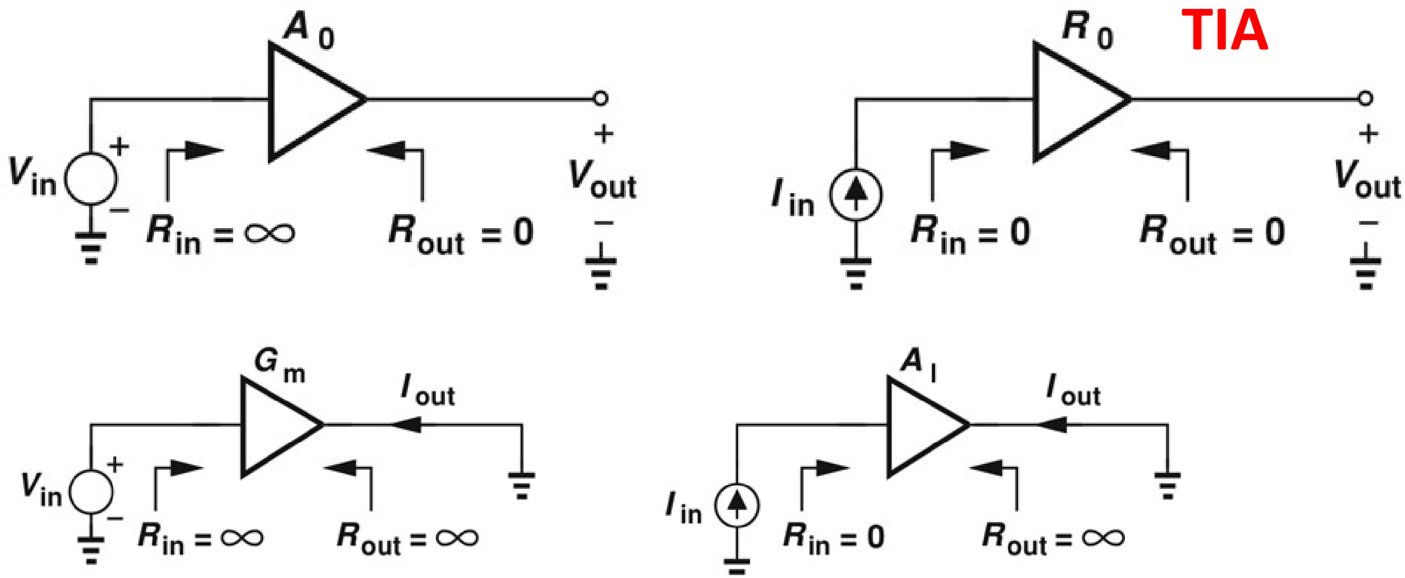

- Reasons for the desirable R_{in} & R_{out}?

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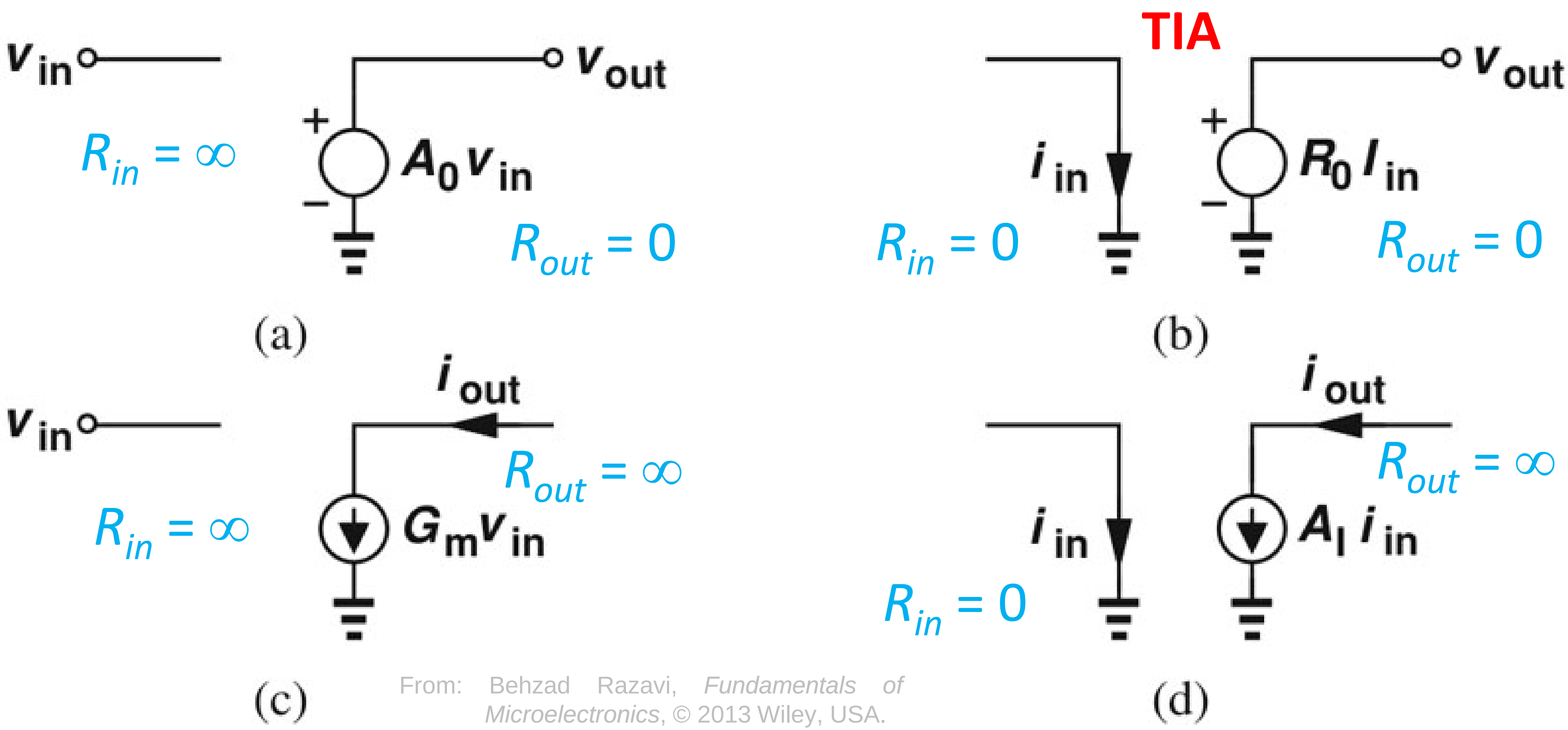
Trans-Impedance Amplifier (TIA)

(4 amplifier types)

- The four types of amplifiers can be modelled as below:



From: Behzad Razavi, *Fundamentals of Microelectronics*, © 2013 Wiley, USA.

- Understood the desirable R_{in} & R_{out}?

Trans-Impedance Amplifier (TIA)

(4 amplifier types)

- ❑ A **trans-impedance amplifier** (**TIA**) is an amplifier that amplifies an input current to produce a voltage output.

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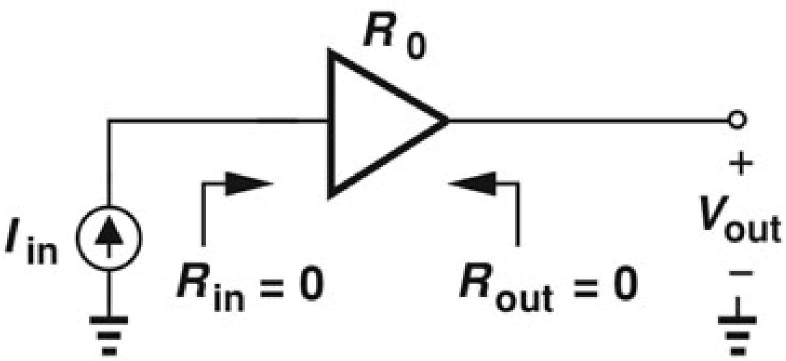


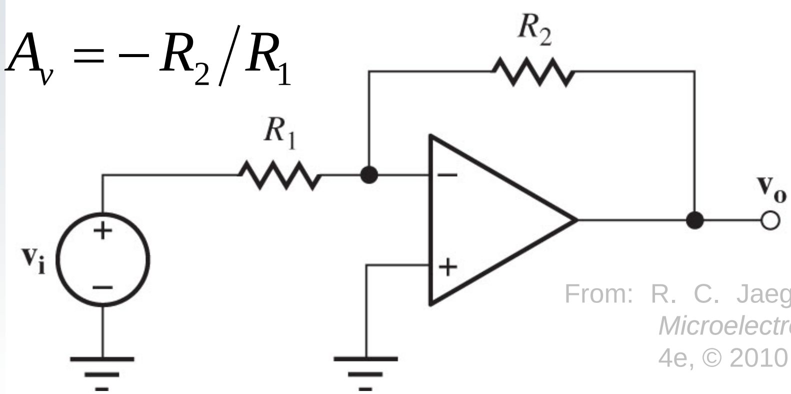
- ➢ In order to allow the input current to all flow into the amplifier, the input impedance should be zero ideally.
- ➢ To deliver the output voltage completely to the next stage (or load), the output impedance should be zero ideally, according to the simple principle of voltage division.
- ➢ The signal gain is $V_{out}/I_{in} = Z$.

Inverting Amplifier

(voltage amplification)

- An **operational amplifier** can be configured as an **inverting amplifier** and a non-inverting amplifier.
  - In both configurations, voltage signals are sensed at the input and produced at the output.
- In the **inverting amplifier** configuration, the positive input of the op amp is grounded and a feedback network of resistors (R_1 & R_2) connects the negative input, the output and the signal source.

$$A_v = -R_2/R_1$$



- At low frequencies, the voltage gain is $A_v = -R_2/R_1$, $R_{in} = R_1$, and $R_{out} = 0$ with an ideal op amp.

From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

Non-Inverting Amplifier

(voltage amplifier with desirable R_{in} & R_{out})

- In the **non-inverting amplifier** configuration, the input voltage signal is applied to the positive input of the op amp and part of the output voltage signal is fed back to the negative input of the op amp through a voltage dividing network (R_1 & R_2).

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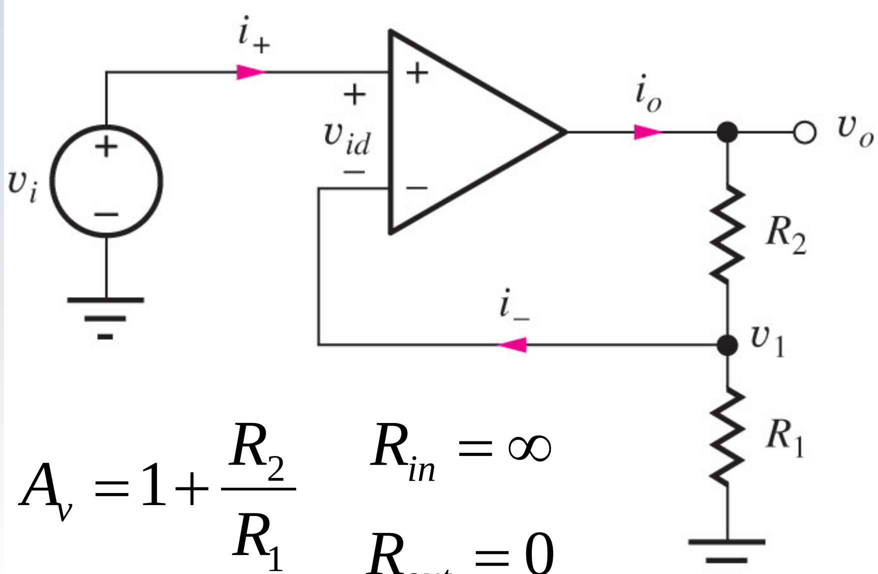

$$A_v = 1 + \frac{R_2}{R_1} \qquad R_{in} = \infty \qquad R_{out} = 0$$

- At low frequencies, the voltage gain is A_v = 1+R_2/R_1, R_{in} = ∞, and R_{out} = 0 with an ideal op amp.
- Such a voltage amplifier has very desirable R_{in} and R_{out}.

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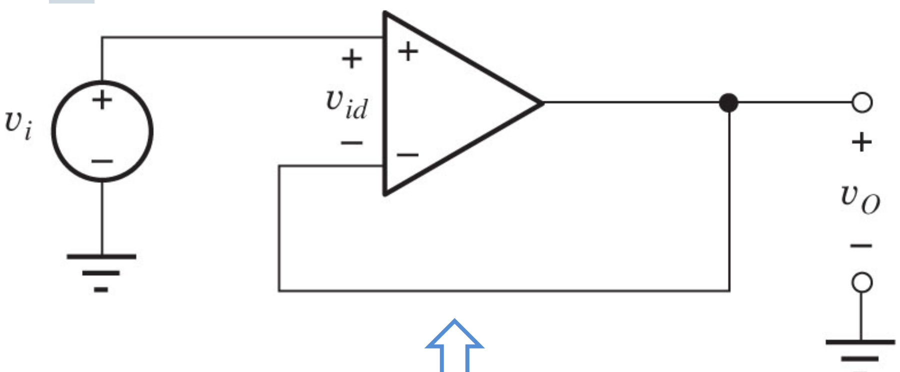
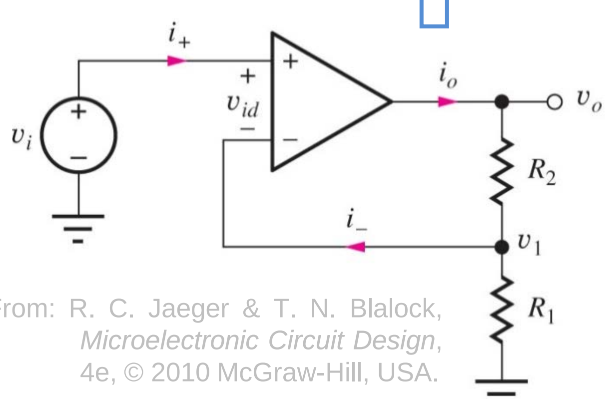
Non-Inverting Amplifier

(voltage follower with desirable R_{in} & R_{out})

- In the **non-inverting amplifier** configuration, if R_2 = 0 and R_1 = ∞ in the voltage dividing network, it becomes a **voltage follower** with the desirable desirable R_{in} and R_{out} despite the voltage gain is just 0 dB (i.e. unity gain).



- The **voltage follower** is useful as a buffer in analogue signal processing circuits.
  - It is like the **source-follower** & **emitter-follower** configurations in transistor amplifiers.



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$$A_v = 1 + \frac{R_2}{R_1}$$

$$R_{in} = \infty \qquad R_{out} = 0$$

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Inverting Amplifier – other uses

(integrator & differentiator)

- In voltage amplification, the **inverting amplifier** configuration is considerably worse than the **non-inverting amplifier** counterpart. It doesn't mean it's no good. They can have other uses rather than just voltage amplification.

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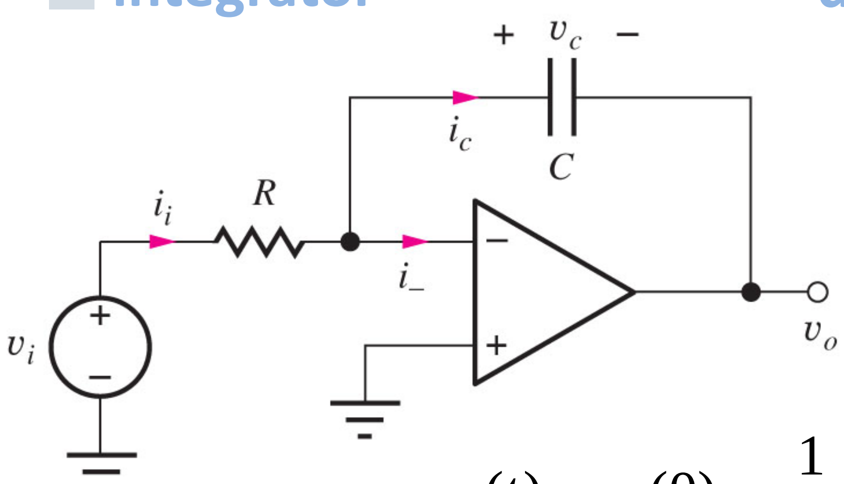
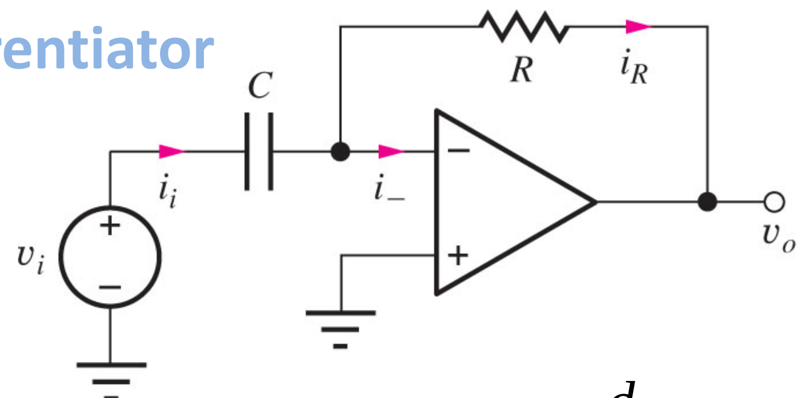
integrator



$$v_o(t) = v_o(0) - \frac{1}{RC}\int_0^t v_i(\tau)d\tau$$

differentiator



$$v_o(t) = -RC\frac{d}{dt}\left(v_i(t)\right)$$

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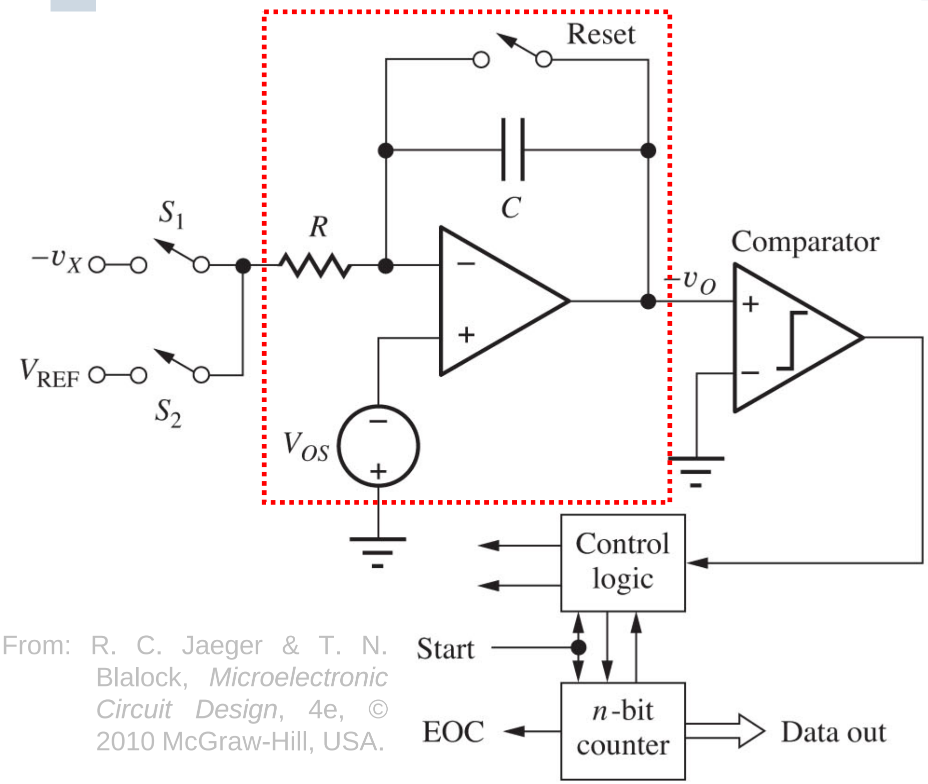
Inverting Amplifier – other uses

(summing amplifier & DAC)

- ❑ In fact, the **inverting amplifier** configuration is also useful in some other signal processing circuits.

integrator in a dual-ramp ADC



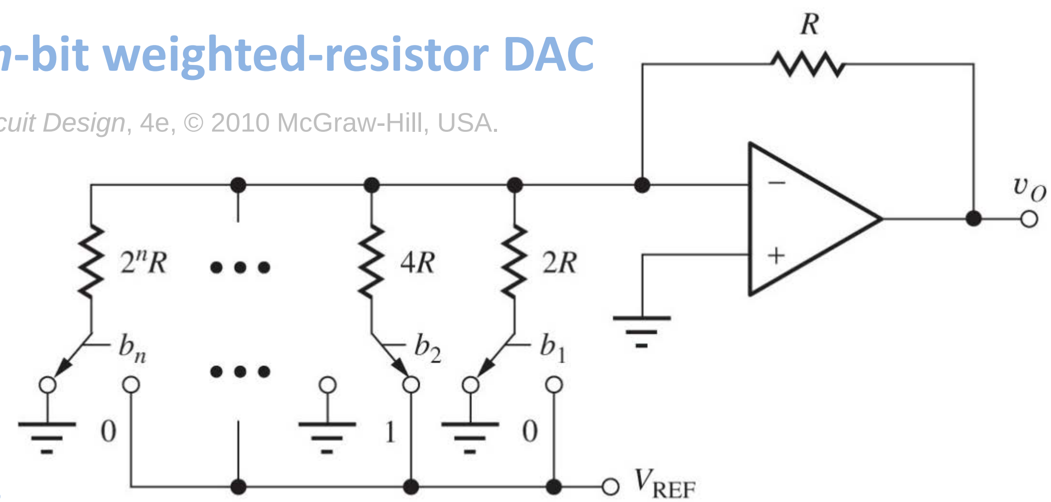
From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

- ❑ The **integrator** constructed from the **inverting amplifier** is a highly useful building block for making an analogue-to- digital converter (ADC). An ADC is indispensable in converting analogue electrical signals into digital data for digital signal processing and storage.

Inverting Amplifier – other uses
(summing amplifier & DAC)

- The **inverting amplifier** configuration can also be used easily as a **summing amplifier** which can be expanded for making a digital-to-analogue converter (DAC). A DAC is indispensable in processing electrical signals in the world of digital media.

n-bit weighted-resistor DAC



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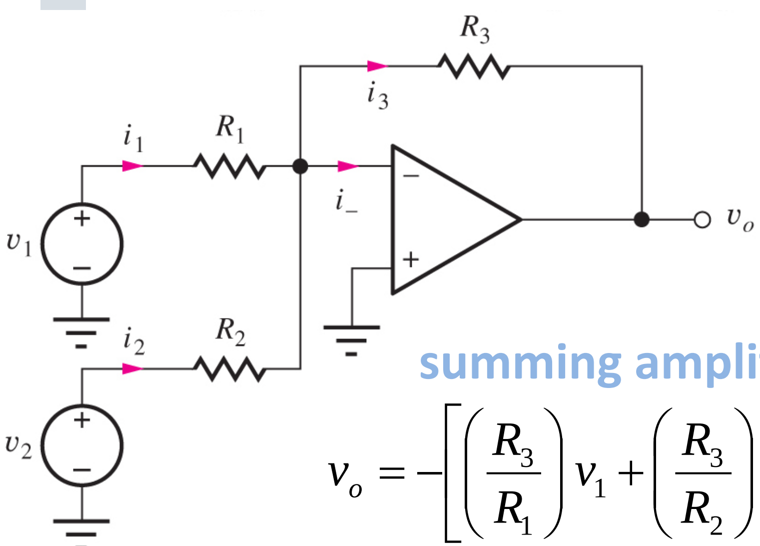

summing amplifier

$$v_o = -\left[\left(\frac{R_3}{R_1}\right)v_1 + \left(\frac{R_3}{R_2}\right)v_2\right]$$

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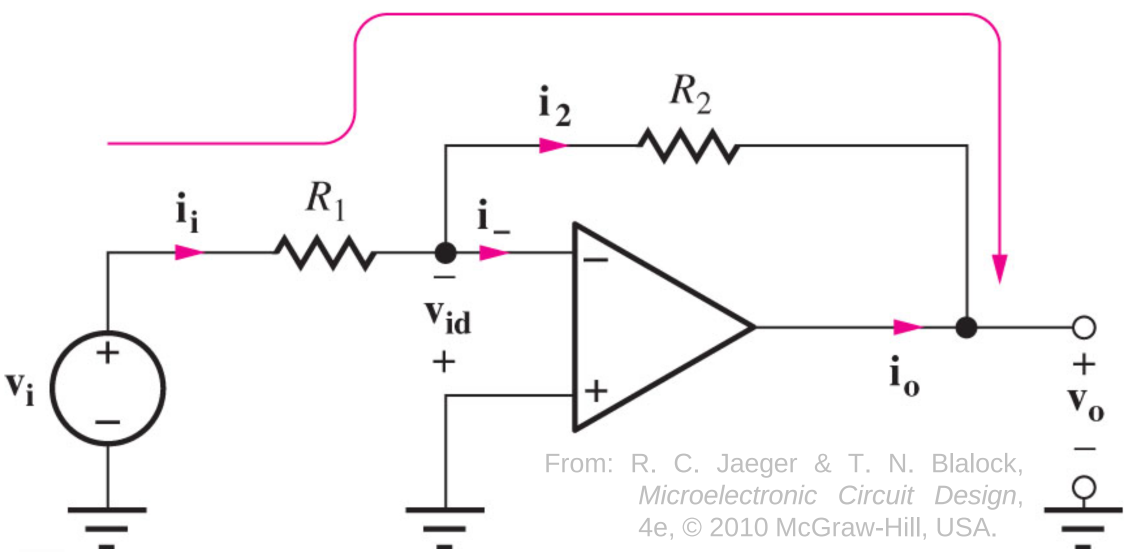
Inverting Amplifier as TIA

(current flow)

- The **inverting amplifier** can be used as a **trans-impedance amplifier** (**TIA**) by modifying the input configuration.
  - The negative input terminal of the op amp is a **virtual ground** (as $v_{id} \approx 0$ V when the positive input is grounded).
  - The input current is $i_i = v_i/R_1$.
  - The *ideally* high input impedance of the op amp makes i_i flow through R_2.



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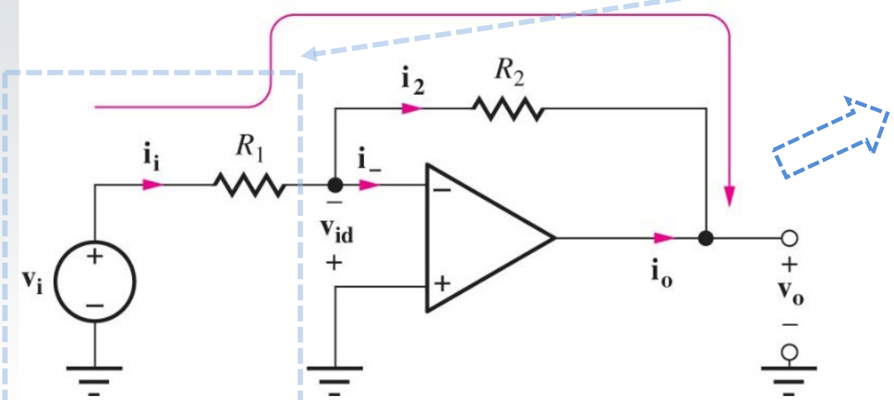
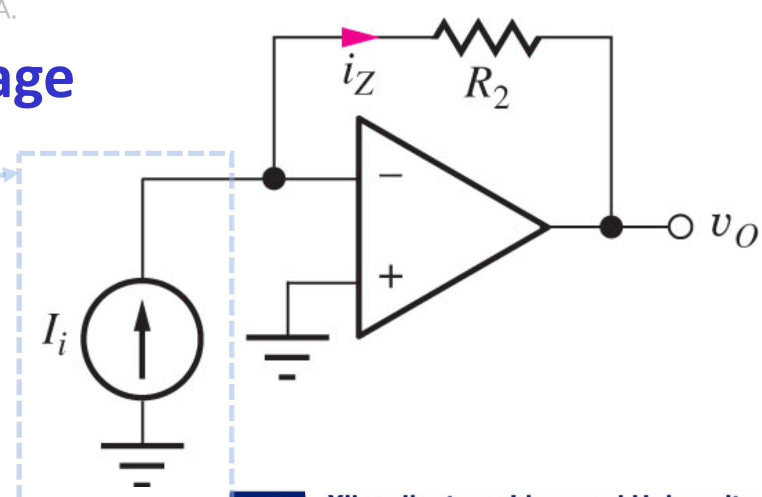
Inverting Amplifier as TIA

(current-to-voltage amplification)

- The input current can be injected directly in the **inverting amplifier** and then the signal would be amplified to a voltage signal at the output.
  - The voltage source v_i and resistor R_1 are replaced by an input current I_i.
  - It is hence a **current-to-voltage (I-V) amplifier/converter**.

From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

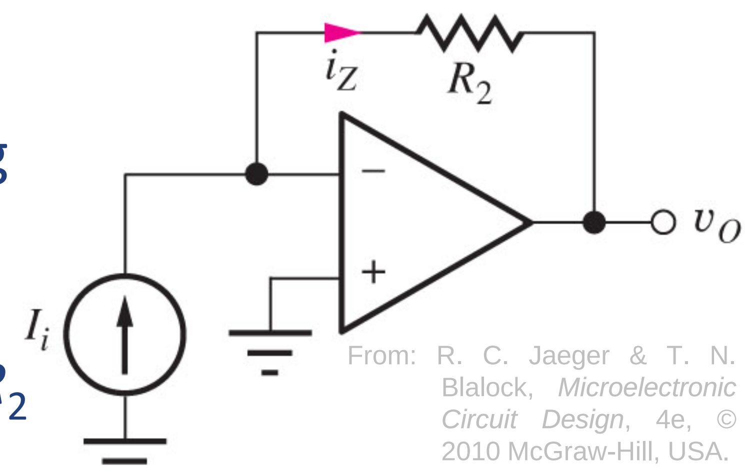




Inverting Amplifier as TIA

(transimpedance gain in unit Ω)

- In the TIA configured from the **inverting amplifier**, the DC gain is obviously the feedback resistance linking the output to the input i.e. $A_{TIA} = v_O/I_i = -R_2$.
  - $I_i = i_Z$ as the *ideally* high input impedance of the op amp makes I_i flow through R_2.
  - With the negative input terminal of the op amp being a **virtual ground** (as $v_{id} \approx 0$ V with the positive input terminal grounded), $v_O = -i_Z R_2$ according to Ohm's law.
  - The unit of the signal gain A_{TIA} is Ω.

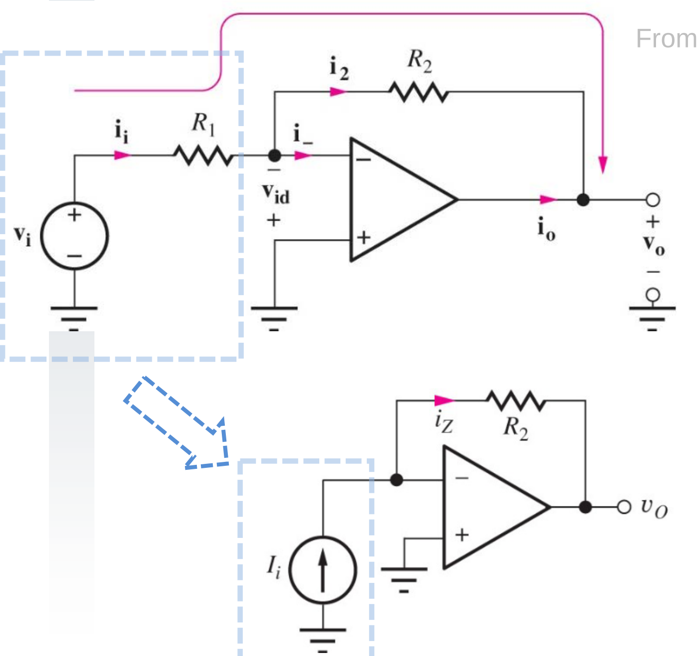


From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

Inverting Amplifier as TIA

(resistance ***R*** generalised to impedance ***Z***)

- In configuring the **inverting amplifier** as a TIA, instead of having only resistors, there can be capacitors (and inductors) in the circuit in general.
  - Similar circuit analysis can be performed to find out the frequency-dependent signal gain by considering ***Z***.



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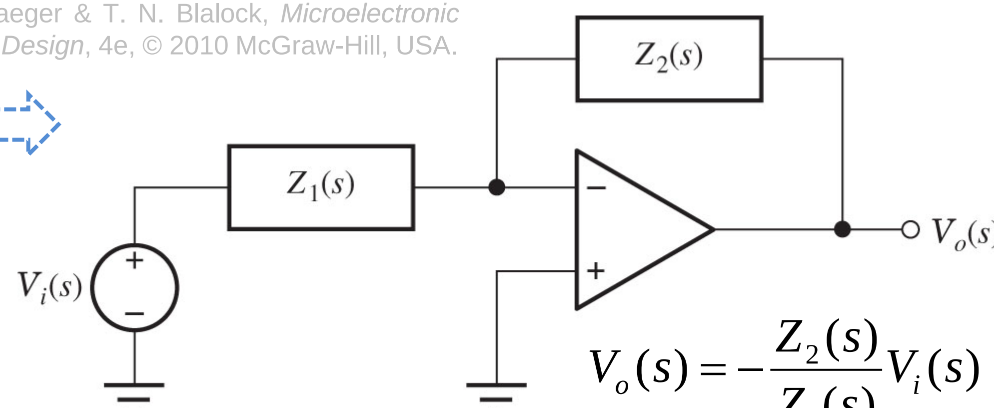

$$V_o(s) = -\frac{Z_2(s)}{Z_1(s)} V_i(s)$$

$s = j\omega$

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Transimepedance Amplifier

(circuit analysis with input capacitance)

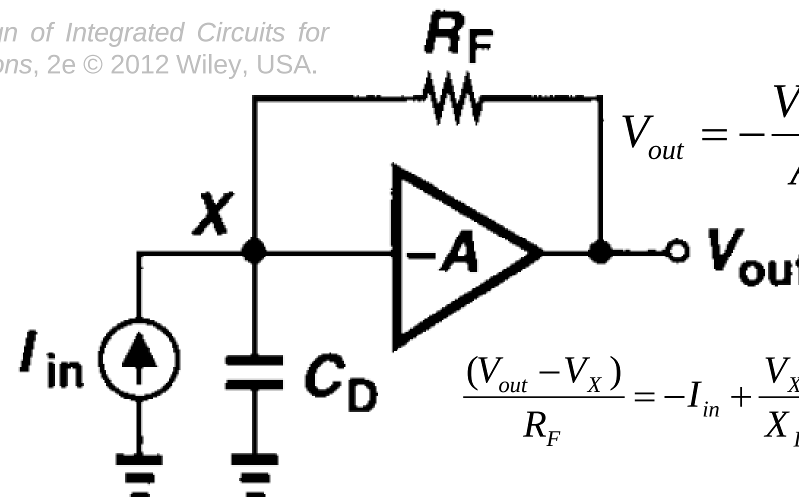
- When a **TIA** is used for amplifying a current signal from a photodiode, there is usually a <u>non-negligible</u> capacitance C_D associated with the photodiode.

From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

$$A_{TIA} = \frac{V_{out}(s)}{I_{in}(s)} = -\frac{A}{A+1} \cdot \frac{R_F}{1+\left(\frac{R_F C_D}{A+1}\right)s}$$

$$\frac{V_{out}(s)}{I_{in}(s)} \approx -\frac{R_F}{1+\left(\frac{R_F C_D}{A}\right)s} = \frac{R_F}{1+\frac{j\omega}{\omega_{3dB}}}$$

$$\omega_{3dB} = \frac{A}{R_F C_D} \text{ or } f_{3dB} = \frac{A}{2\pi(R_F C_D)}$$



$$V_{out} = -\frac{V_X}{A}$$

$$\frac{(V_{out} - V_X)}{R_F} = -I_{in} + \frac{V_X}{X_D}$$

$$\frac{(V_{out} + V_{out}/A)}{R_F} = -I_{in} - \frac{V_{out}/A}{1/(sC_D)}$$

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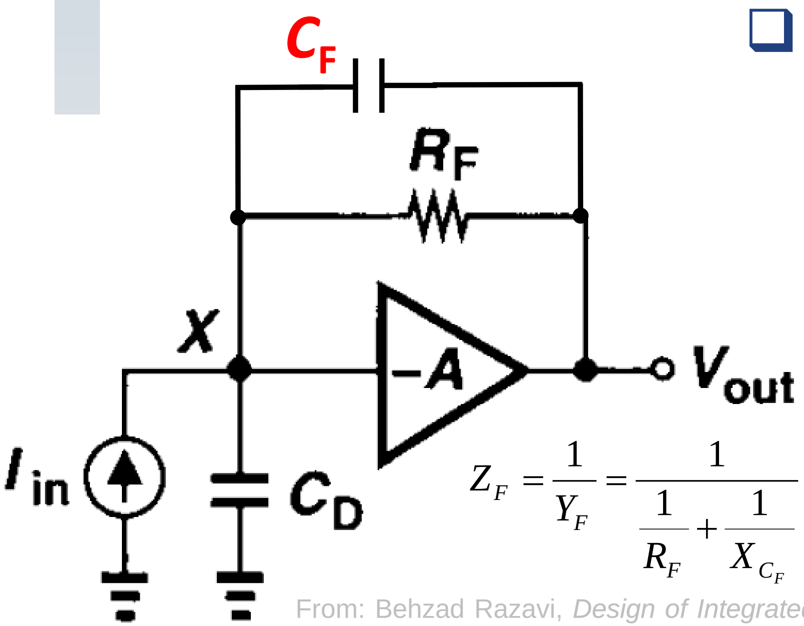
Transimepedance Amplifier

(feedback capacitor added for stability)

- In the first-order analysis, the **inverting amplifier** in the TIA circuit is assumed to have a constant (open-loop) voltage gain -***A*** which however is frequency dependent –***A***($j\omega$) in reality.



$$Z_F = \frac{1}{Y_F} = \frac{1}{\frac{1}{R_F} + \frac{1}{X_{C_F}}}$$

- To avoid instability of the TIA circuit, a **feedback capacitor** of C_F is usually added.
  - The feedback impedance is

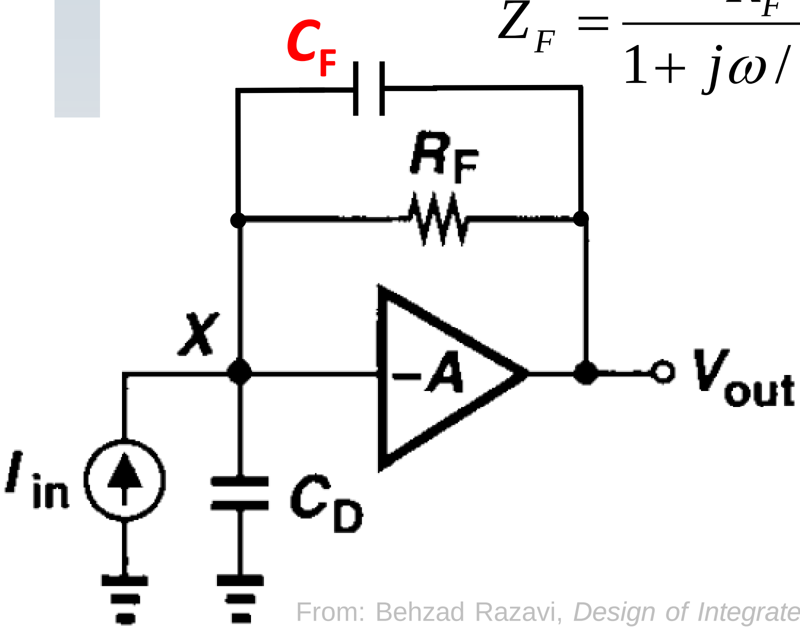
$$Z_F = \frac{1}{\frac{1}{R_F} + j\omega C_F} = \frac{R_F}{1 + j\omega R_F C_F}$$

From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

Transimepedance Amplifier

(feedback capacitance C_F)

- The rule of thumb in avoiding the TIA circuit instability is to choose the C_F value of the **feedback capacitor** such that its associated frequency is the geometric mean of two frequencies: $\omega_{C_F} = \sqrt{\omega_{C_D}\omega_{GX}}$



$$Z_F = \frac{R_F}{1 + j\omega/\omega_{C_F}}$$

$$\omega_{C_D} = \frac{1}{R_F C_D} \quad \text{and} \quad \omega_{C_F} = \frac{1}{R_F C_F}$$

- ω_{GX} is the **gain-bandwidth product** of the ***open-loop*** **inverting amplifier** (i.e. the frequency at which the open-loop gain becomes 0 dB).

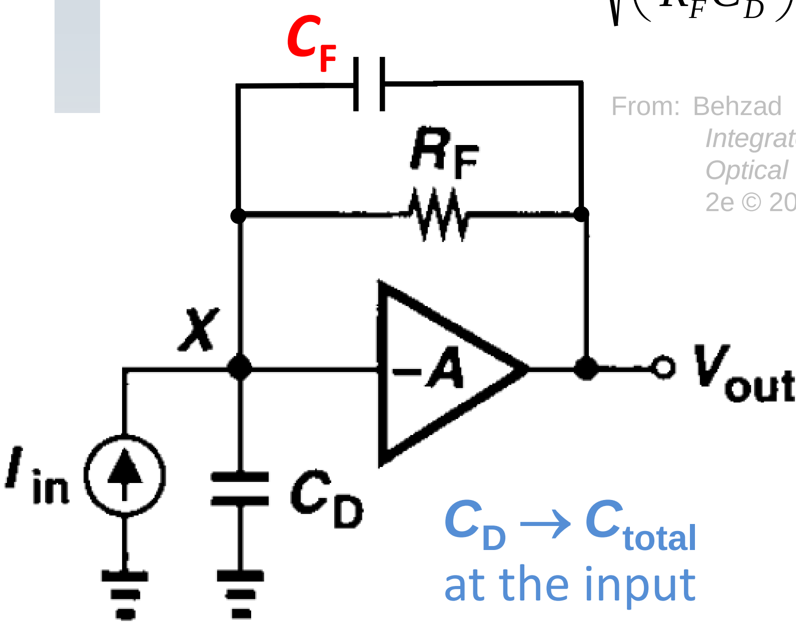
From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

Transimepedance Amplifier

(C_F related to gain bandwidth product)

- So to avoid circuit instability, the C_F value of the **feedback capacitor** in the TIA should be:

$$C_F = \frac{1}{R_F\sqrt{\left(\frac{1}{R_F C_D}\right)\cdot\omega_{GX}}} = \frac{1}{\sqrt{\left(\frac{R_F}{C_D}\right)\cdot\omega_{GX}}} = \sqrt{\left(\frac{C_D}{R_F\,\omega_{GX}}\right)}$$



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

$$\boxed{C_F = \sqrt{\frac{C_D}{2\pi f_{GX} R_F}}}$$

$C_D \rightarrow C_{total}$ at the input

- In general, the capacitance C_D should include all the capacitances at the input.

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Transimepedance Amplifier

(design guidelines)

- To design and construct a TIA using the inverting amplifier configuration, the following guidelines can be followed:
  - choose a suitable photodiode for detecting optical signals
  - determine the required **transimpedance gain** from the output current of the photodiode and the desirable output voltage (e.g. DC gain of A_{TIA}=100 kΩ for v_{out}=10 mV and i_{in}=100nA) hence fixing $\boldsymbol{R_F}$ for the feedback resistor
  - choose an op amp with its open-loop **gain bandwidth product** f_{GX} well above the frequency of interest for signal amplification
  - determine $\boldsymbol{C_F}$ for the feedback capacitor by finding out the photodiode capacitance C_D, and other input parasitic capacitances

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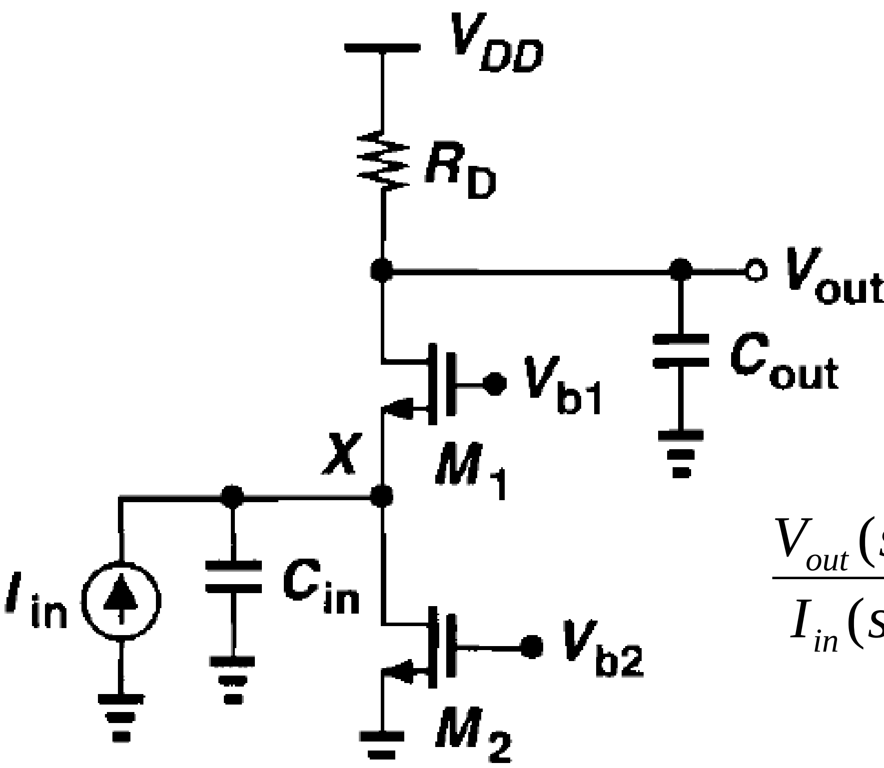
Transimepedance Amplifier

(construction from transistor amplifiers)

- Apart from using an inverting amplifier, a **transimpedance amplifier** (TIA) can also be designed and constructed using the fundamental transistor amplifier configurations.



- Can you recognise which basic transistor amplifier configuration it is in the TIA circuit here?
- Why such configuration is used instead of other two?

$$\frac{V_{out}(s)}{I_{in}(s)} = \frac{g_{m1}R_D}{(g_{m1} + sC_{in})(sR_D C_{out} + 1)}$$

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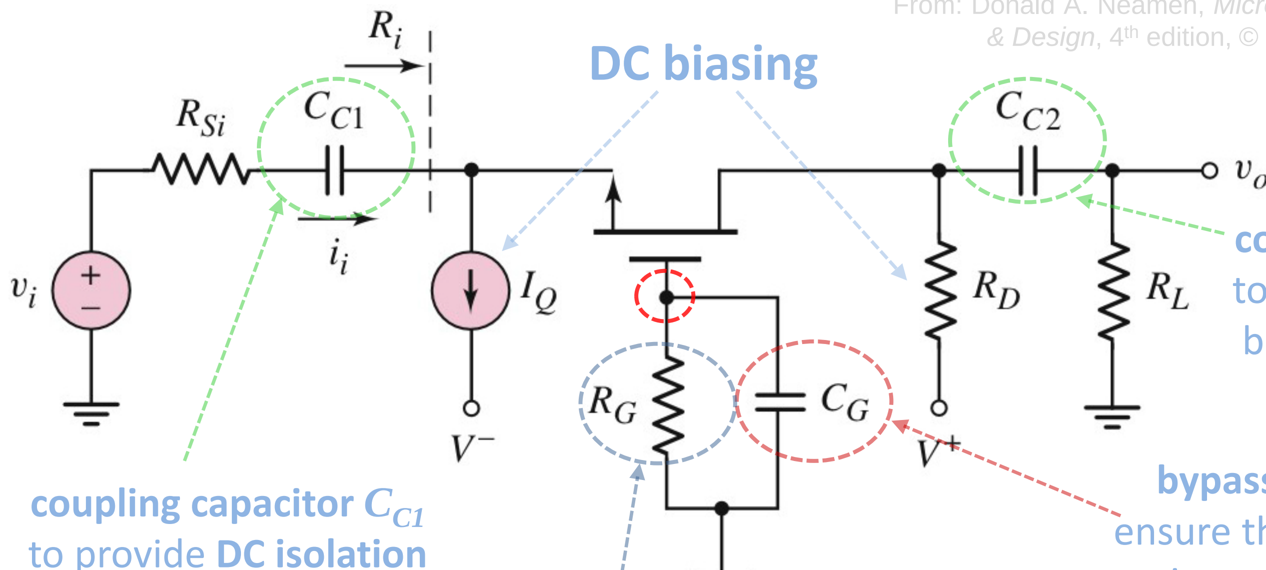
Common-Gate Amplifier for TIA

(input signal applied to the source)

- Among the three basic FET amplifiers, the common-gate configuration has the input signal applied to the source and <u>the gate is at signal ground</u>, and the output current drives a load resistor.

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.



coupling capacitor C_{C1} to provide <u>**DC isolation**</u> between the input signal source and the amplifier circuit

gate resistor to prevent the build-up of static charge on the gate terminal

coupling capacitor C_{C2} to provide <u>**DC isolation**</u> between the load and the drain terminal

bypass capacitor to ensure the gate terminal is at signal ground

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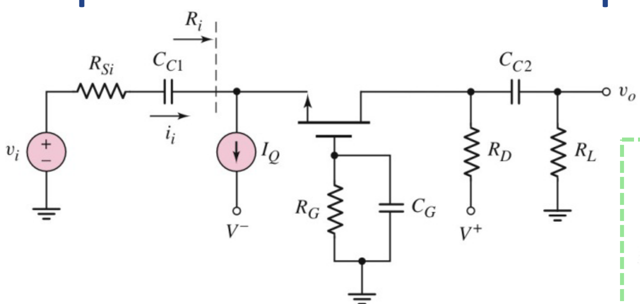
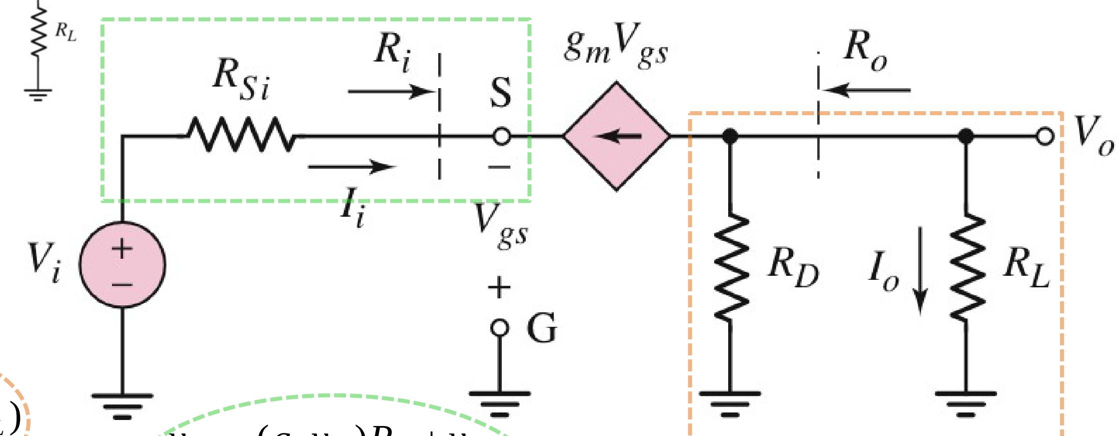
Common-Gate Amplifier for TIA

(small-signal equivalent circuit & voltage gain)

- Same as before, representing the common-gate circuit by a **small-signal equivalent circuit, AC analysis** can be performed after simplifying the equivalent circuit further.



From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.



$$\frac{v_{gs}}{v_i} = -\frac{1}{1+g_mR_{Si}}$$

$$\frac{v_o}{v_{gs}} = -g_m(R_D \| R_L)$$

$$v_i = -(g_m v_{gs})R_{Si} + v_{sg}$$
$$v_i = -(g_m v_{gs})R_{Si} - v_{gs}$$
$$v_i = -v_{gs}(g_mR_{Si} + 1)$$

$$v_o = -(g_m v_{gs})(R_D \| R_L)$$

$$A_v = \frac{g_m(R_D \| R_L)}{1+g_mR_{Si}}$$

Note: **As A_v is positive, the output and input signals are *in phase*.**

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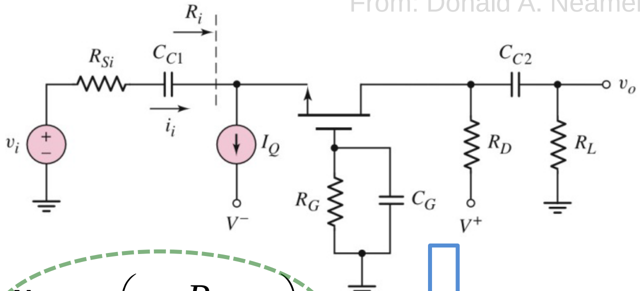
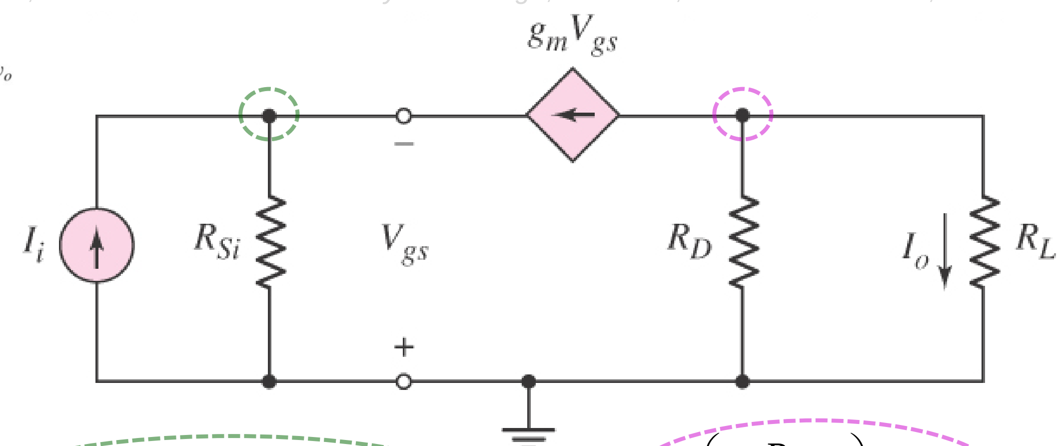
Common-Gate Amplifier for TIA

(small-signal current gain)

- In some cases, the signal input to a common-gate circuit is a current. Then we need to calculate the current gain also using the **small-signal equivalent circuit**, but with a **Norton equivalent circuit** as the signal source.

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.





$$\frac{v_{gs}}{i_i} = -\left(\frac{R_{Si}}{1+g_m R_{Si}}\right)$$

$$\frac{i_o}{v_{gs}} = -g_m\left(\frac{R_D}{R_D+R_L}\right)$$

$$i_i = \frac{v_{sg}}{R_{Si}} + (-g_m v_{gs}) = -\frac{v_{gs}}{R_{Si}} - g_m v_{gs}$$

$$i_o = \left(\frac{R_D}{R_D+R_L}\right)(-g_m v_{gs})$$

$$A_i = \frac{i_o}{i_i} = \left(\frac{R_D}{R_D+R_L}\right)\left(\frac{g_m R_{Si}}{1+g_m R_{Si}}\right)$$

$$i_i = -v_{gs}\left(\frac{1+g_m R_{Si}}{R_{Si}}\right)$$

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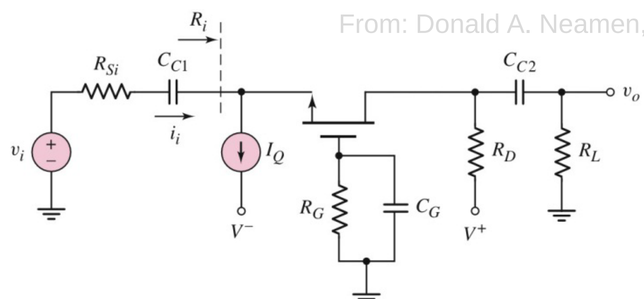
Common-Gate Amplifier for TIA

(current gain)

- In the common-gate amplifier circuit, the current gain is close to unity if $R_D >> R_L$ and $g_m R_{Si} >> 1$:

$$A_i = \frac{i_o}{i_i} = \left(\frac{R_D}{R_D + R_L}\right)\left(\frac{g_m R_{Si}}{1 + g_m R_{Si}}\right) \approx 1 \qquad \text{if } R_D >> R_L \text{ and } g_m R_{Si} >> 1$$



From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.

- Advanced notes: the common-gate amplifier suffers from the ***trade-off*** between the **voltage headroom** and the **signal gain**.
  - To achieve a high gain, it is necessary to have a high biasing drain current I_D or a high R_D.
  - However, the drain voltage, $V_{DS} = V_{DD} - I_D R_D$, must remain above $(V_{GSQ} - V_{TN})$ to ensure that the MOSFET is in the saturation region (i.e. $V_{DS} > V_{DSsat}$).

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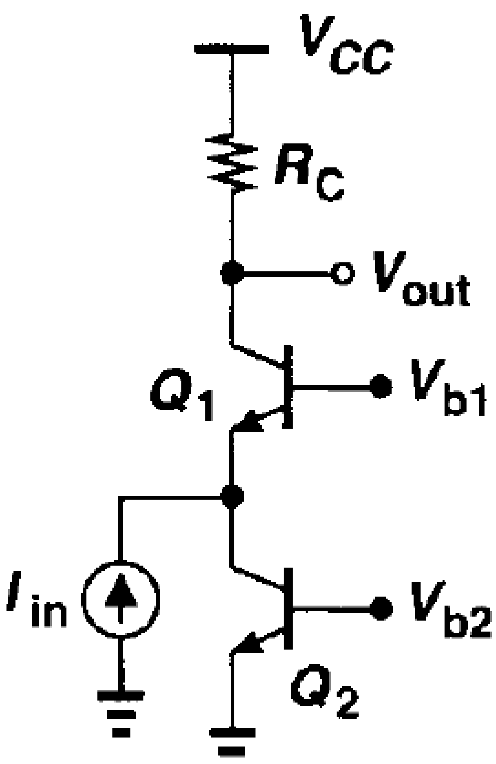
Transimepedance Amplifier

(construction from transistor amplifiers)

- Apart from using an inverting amplifier, a **transimpedance amplifier** (TIA) can also be designed and constructed using the fundamental transistor amplifier configurations.



  - Can you recognise which basic transistor amplifier configuration it is in the TIA circuit here?
  - Why such configuration is used instead of other two?

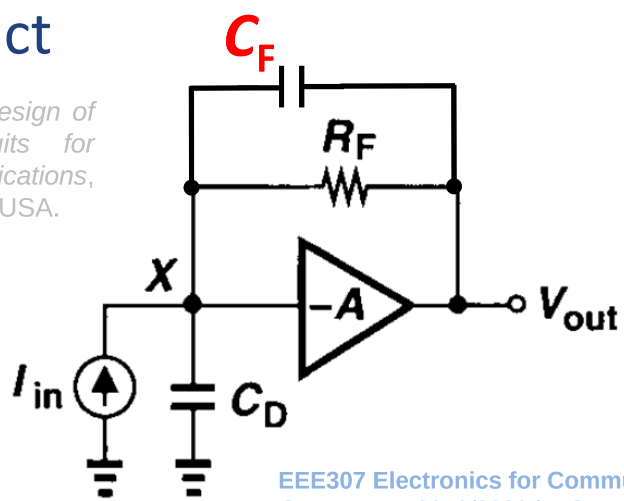
$$\frac{V_{out}(s)}{I_{in}(s)} = \frac{\left[(1+g_{m1}r_o)r_{\pi 1} + r_b\right]R_C}{(1+g_{m1}r_o)r_{\pi 1} + r_b + R_C + r_o}$$

Transimepedance Amplifier

(design guidelines)

- To design and construct a TIA using the inverting amplifier configuration, the following guidelines can be followed:
  - determine the required transimpedance gain from the output current of the photodiode and the desirable output voltage (e.g. DC gain of A_{TIA}=100 kΩ for v_{out}=10 mV and i_{in}=100nA)
  - choose an op amp with its open-loop gain bandwidth product

From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.



$$C_F = \sqrt{\frac{C_D}{2\pi f_{GX} R_F}}$$