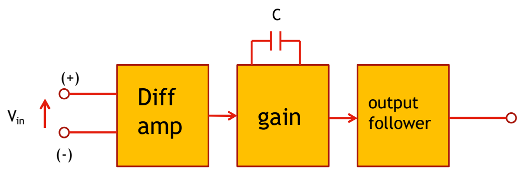
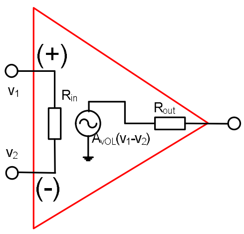
Wrocław University of Technology

Operational Amplifier
Op-Amp

Op-Amp block diagram

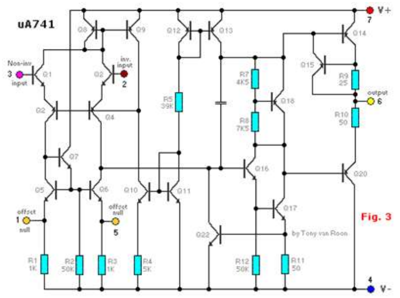


Op-Amp model



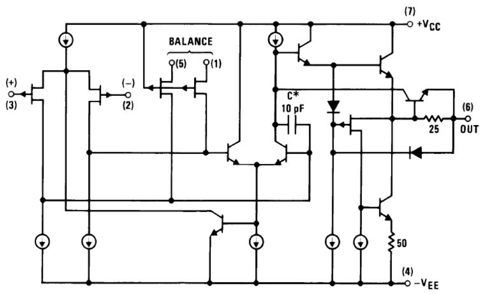
Wroclaw University of Technology

uA741 - inside



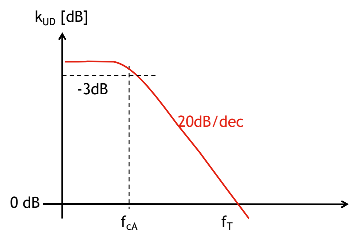
Wroclaw University of Technology

LF155/157

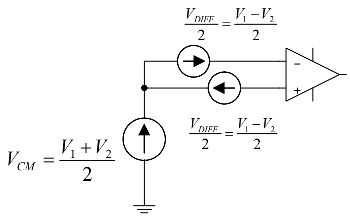


Wroclaw University of Technology

Bandwith
Gain bandwith



Wroclaw University of Technology

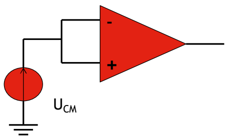


$$V_{out} = A_v V_{DIFF} + \frac{A_v}{CMRR} V_{CM}$$

Wroclaw University of Technology

Common Mode Rejection Ratio

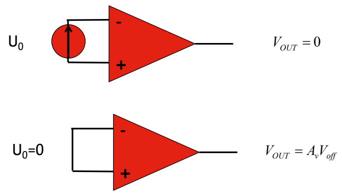
$$V_{out} = A_v V_{DIFF} + \frac{A_v}{CMRR} V_{CM}$$



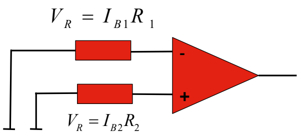
$$V_{OUT} = \frac{AV}{CMRR[V/V]} V_{CM}$$

Wroclaw University of Technology

Input offset voltage



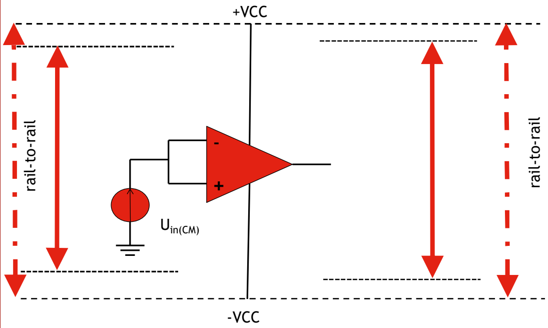
Voltage offset vs. input bias current



$$V_{out(off)} = \left(I_B\left(R+\Delta R\right)-\left(I_B+\Delta I_B\right)R\right)A_v =$$
$$= \left(\Delta I_B R + I_B \Delta R\right)A_v \underset{\Delta R=0}{\approx} \Delta I_B R A_v$$

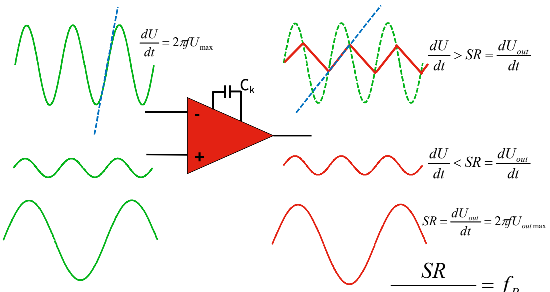
Wroclaw University of Technology

Input and output voltage swing



Wroclaw University of Technology

Slew-Rate
Power bandwith



$$\frac{SR}{2\pi U_{out\,max}} = f_P$$

Wrocław University of Technology

Typical Op-Amp parameters

Parameter	Symbol	Perfect op-amp	uA741	LF157
OL gain	A_{VOL}	infinite	100000	200000
Unity gain frequecy	f_T	infinite	1Mhz	20MHz
Input resistance	R_{in}	infinite	2MΩ	10^{12}Ω
Output resistance	R_{out}	zero	75Ω	100Ω
Input bias	$I_{in(bias)}$	zero	80nA	30pA
Input offset current	$I_{in(off)}$	zero	20nA	3pA
Input offset voltage	$V_{in(off)}$	zero	2mV	1mV
CMRR	CMRR	infinite	90dB	100dB

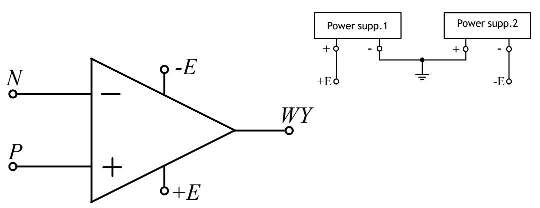
Wrocław University of Technology

More Op-Amp parameters

Type	Manufacturer	Offset-voltage	Bias current	Gain-bandwidth product	Slew rate	Operating voltage min/max	OPs per case	Special feature
VV-OPAmps: Low cost universal types								
…741	Many	1 mV	80 nA	1.5 MHz	0.6 V/µs	6/36 V	1	high voltage
…324	Many	2 mV	45 nA	1 MHz	0.6 V/µs	3/32 V	4	single supply
AD8034	Analog D.	1 mV	1 pA	80 MHz	80 V/µs	5/24 V	2	fast
AD8058	Analog D.	1 mV	0.5 µA	325 MHz	1000 V/µs	3/12 V	2	damned fast
AD8604	Analog D.	1 mV	0.2 pA	8 MHz	5 V/µs	3/ 6 V	4	RRIO
AD8619	Analog D.	0.5 mV	0.2 pA	0.4 MHz	0.1 V/µs	2/ 5 V	4	RRIO
AD8674	Analog D.	20 µV	5 nA	10 MHz	4 V/µs	8/36 V	4	$V_{nd} = 3nV/\sqrt{Hz}$
ADA4851	Analog D.	0.6 mV	2 µA	130 MHz	375 V/µs	3/10 V	4	RRO
OP177	Analog D.	20 µV	1 nA	0.6 MHz	0.3 V/µs	6/36 V	1	Low offset
LTC6242	Lin. Tech.	50 µV	1 pA	18 MHz	10 V/µs	3/ 6 V	4	$V_{nd} = 7nV/\sqrt{Hz}$
MAX4094	Maxim	30 µV	20 nA	0.5 MHz	0.2 V/µs	3/ 6 V	4	RRIO
MAX4351	Maxim	1 mV	8 µA	200 MHz	490 V/µs	9/11 V	2	RRO, fast
MAX4495	Maxim	0.3 mV	0.2 µA	5 MHz	3 V/µs	5/12 V	4	RRO
MAX9916	Maxim	0.2 mV	1 pA	1 MHz	0.5 V/µs	2/ 6 V	2	RRIO
LF356	National	1 mV	30 pA	5 MHz	12 V/µs	8/36 V	1	robust
LMC6034	National	1 mV	40 fA	1.4 MHz	1 V/µs	5/15 V	4	low bias
LMC6484	National	0.1 mV	20 fA	1.5 MHz	1 V/µs	3/15 V	4	RRIO
LMH6646	National	1 mV	0.4 µA	55 MHz	22 V/µs	3/12 V	2	RRIO
OPA2244	Texas I.	1 mV	10 nA	0.3 MHz	0.1 V/µs	2/36 V	2	$I_6 = 40\,\mu A$
OPA4134	Texas I.	0.5 mV	5 pA	8 MHz	20 V/µs	5/36 V	4	low distortion
OPA4343	Texas I.	2 mV	0.2 pA	5 MHz	6 V/µs	3/ 6 V	4	RRIO
TLC084	Texas I.	0.4 mV	3 pA	10 MHz	16 V/µs	5/16 V	4	single supply
TLC274	Texas I.	1 mV	0.1 pA	2 MHz	3 V/µs	3/16 V	4	single supply

Wrocław University of Technology

Op-Amp – power supply



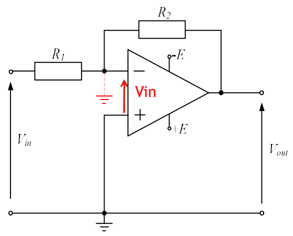
Wroclaw University of Technology

Op-Amp common applications

- inverting amp,
- Non-inverting amp
- summing amp
- substracting amp
- integrator
- differentiator

Wroclaw University of Technology

Inverting Amp virtual ground



For a perfekt OA:

$$A_{vOL} = \infty$$

$$r_{in} = \infty$$

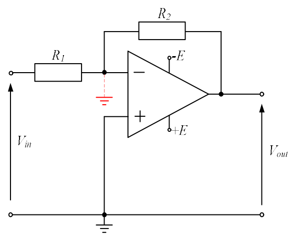
so:

$$V_{in} = \frac{V_{out}}{A_{vOL}} = \frac{V_{out}}{\infty} = 0$$

$$I_{in} = \frac{V_{in}}{r_{in}} = \frac{V_{in}}{\infty} = 0$$

Wroclaw University of Technology

Inverting Amp



$$I_{in} = \frac{V_{in}}{R_1} \qquad I_{out} = \frac{V_{out}}{R_2}$$

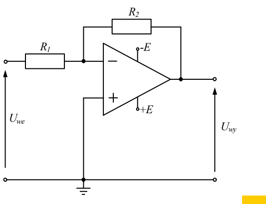
$$I_{in} = -I_{out}$$

$$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_2}$$

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

Wroclaw University of Technology

inverting amp (in detail)



$$A_v = -\frac{R_2}{R_1}\frac{1}{1+\dfrac{R_1+R_2}{A_{vOL}R_1}} \approx -\frac{R_2}{R_1}$$

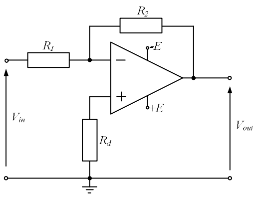
$$R_{in} = R_1 \frac{1}{1+\left|\dfrac{A_v}{A_{vOL}}\right|} \approx R_1$$

$$R_{out} = R_{out0}\frac{R_1+R_2}{R_1(1+A_{vOL})+R_2} \approx R_{out0}\left|\frac{A_v}{A_{vOL}}\right|$$

$$f_2 \approx \frac{f_T}{A_v}$$

Wroclaw University of Technology

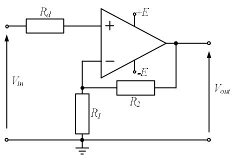
Bias current compecsation



$$R_d = \frac{R_1 R_2}{R_1 + R_2}$$

Wroclaw University of Technology

non-inverting amp



$$R_d = \frac{R_1 R_2}{R_1 + R_2}$$

$$A_v = \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{R_1+R_2}{A_{vOL}R_1}} \approx 1+\frac{R_2}{R_1}$$

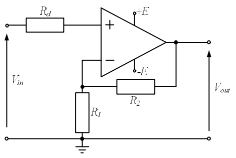
$$R_{in} = R_{in0}$$

$$R_{out} = \frac{R_{out0}}{A_{vOL}}$$

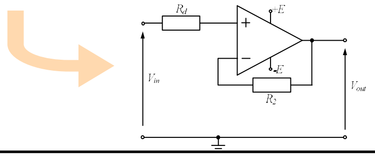
$$f_2 \approx \frac{f_T}{A_v}$$

Wroclaw University of Technology

Follower



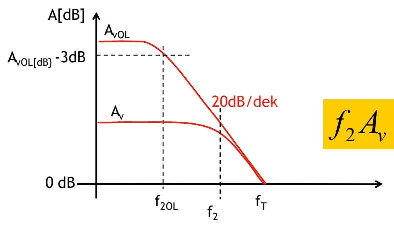
$$A_v = \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{R_1+R_2}{A_{vOL}R_1}} \approx 1+\frac{R_2}{R_1}$$



$$f_2 = f_T$$

Wroclaw University of Technology

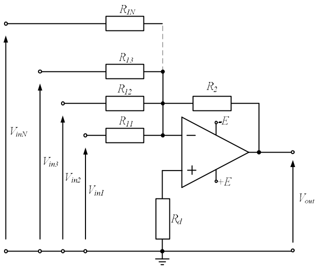
Frequency characteristic



$$f_2 A_v = f_T \bullet "1"$$

Wroclaw University of Technology

Summing amp



$$V_{out} = -R_2\sum_{k=1}^{N}\frac{V_{ink}}{R_{1k}} = -\left(V_{in1}\frac{R_2}{R_{11}} + V_{in2}\frac{R_2}{R_{12}} + V_{in3}\frac{R_2}{R_{13}} + \ldots + V_{inN}\frac{R_2}{R_{1N}}\right)$$

Sumator odwracający

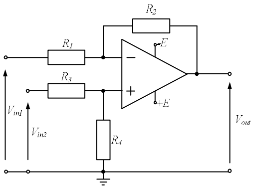
$$V_{out} = -R_2 \sum_{k=1}^{N} \frac{V_{ink}}{R_{1k}} = -\left(V_{in1} \frac{R_2}{R_{11}} + V_{in2} \frac{R_2}{R_{12}} + V_{in3} \frac{R_2}{R_{13}} + \ldots + V_{inN} \frac{R_2}{R_{1N}} \right)$$

when: $R_{11} = R_{12} = R_{13} = \ldots . = R_{1N} = R_1$

$$V_{out} = -\frac{R_2}{R_1} \left(V_{in1} + V_{in2} + V_{in3} + \ldots + V_{inN} \right)$$

$$R_d = R_2 \| R_{11} \| R_{12} \| R_{13} \| .. \| R_{1N}$$

Substractor
(DIFFERENCE AMPLIFIER)



$$V_{out} = V_{in2} \left(\frac{R_1 + R_2}{R_3 + R_4} \right) \frac{R_4}{R_1} - V_{in1} \frac{R_2}{R_1}$$

when: $R_1 = R_3$ and $R_2 = R_4$

$$V_{out} = \frac{R_2}{R_1} \left(V_{in2} - V_{in1} \right)$$

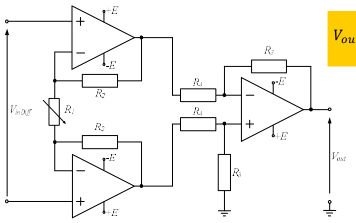
$$R_{in1} \approx R_1$$

$$R_{in2} = R_3 + R_4$$

Substractor with reference
(DIFFERENCE AMPLIFIER with reference)

Wroclaw University of Technology

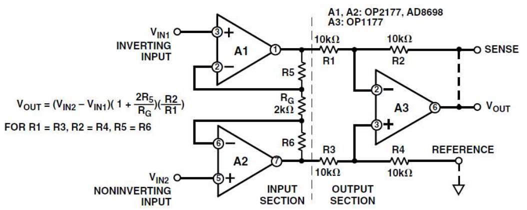
Instrumentation Amp



$$V_{out} = \left(1 + 2\frac{R_2}{R_1}\right)\frac{R_3}{R_4}V_{inDiff}$$

Wroclaw University of Technology

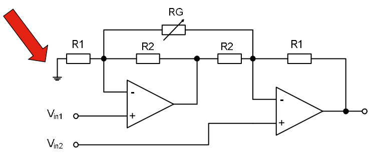
Instrumentation Amp



Wroclaw University of Technology

Instrumentation Amp

offset voltage can be applied

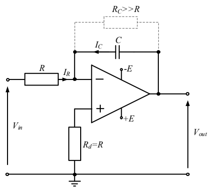


$$V_{out} = (V_{in2} - V_{in1})\left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G}\right)$$

Wroclaw University of Technology

Integrator

$$I_R = \frac{V_{in}(t)}{R} \qquad I_C = C\frac{dV_{out}(t)}{dt}$$



$$I_R + I_C = 0$$

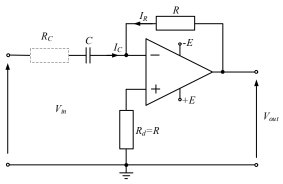
$$V_{out}(t) = -\frac{1}{RC}\int V_{in}(t)dt + U_0$$

$$V_{out} = -\frac{V_{in}}{R_1 C}t + U_0$$

Wroclaw University of Technology

Differentiator

$$I_C = C\frac{dV_{in}(t)}{dt} \qquad I_R = \frac{V_{out}(t)}{R}$$

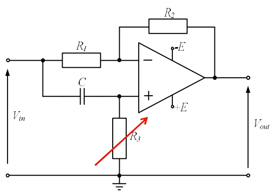


$$I_R + I_C = 0$$

$$V_{out}(t) = -RC\frac{dV_{in}(t)}{dt}$$

Wroclaw University of Technology

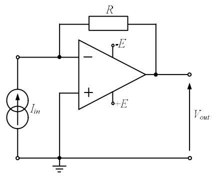
phase shifter (all pass filter of 1st order)



$$\frac{V_{out}}{V_{in}} = -\frac{1 - sCR_3}{1 + sCR_3}$$

Wroclaw University of Technology

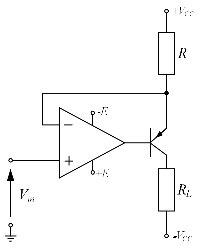
current – voltage transducer



$$V_{out} = -I_{in}R$$

Wroclaw University of Technology

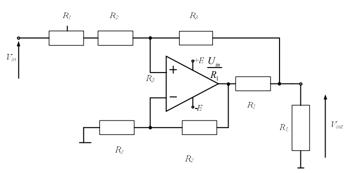
Voltage – current transducer



$$I_L = \frac{V_{CC} - V_{in}}{R}$$

Wroclaw University of Technology

Voltage – current transducer (2)

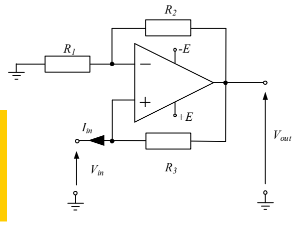


$$I_L = \frac{V_{in}}{R_1} + \frac{R_2 - R_3}{R_1 R_3} V_{out} \underset{R_2 = R_3}{=} \frac{V_{in}}{R_1}$$

Wroclaw University of Technology

INIC
(Current Negative Impedance Converter)

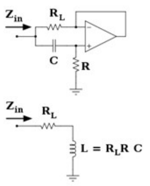
$$I_{in} = \frac{V_{out} - V_{in}}{R_3} = \frac{V_{in}\left(\frac{R_2}{R_1} + 1\right) - V_{in}}{R_3} = \frac{R_2}{R_3 R_1}$$

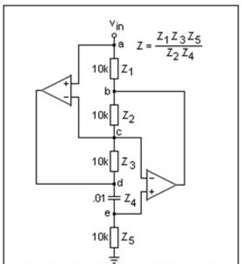


$$R_{in} = -R_3 \frac{R_2}{R_1}$$

Wroclaw University of Technology

Gyrator

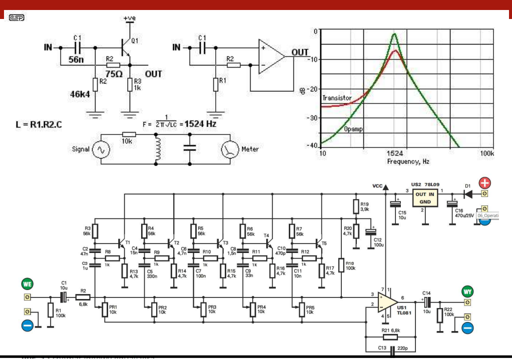




Gyrator Simulating a 1 H Inductor

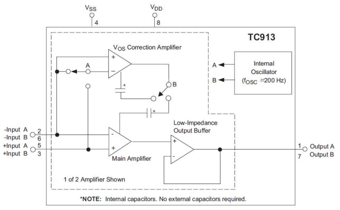
Wroclaw University of Technology

Gyrator



Wrocław University of Technology

Auto-zero Amp ???



TIPs:
- low operatin frequency,
- very low offset

Wrocław University of Technology

Summing up

- real and perfect Op-Amp parameters (CMRR, SR, OFFSET, Uin(RR), Uout(RR), f_T)
- applications:
  - inverting and non-inverting amp,
  - summing amp and subtracting amp,
  - instrumentation amp,
  - integrator and differentiator,
  - idea of an auto zero amp ??