Feedback

With integrated circuit amplifiers, it is possible to come close to ideal characteristics.

R_i can be very large: 1 MΩ – 1 GΩ

R_o can be quite small: 1 Ω – 100 Ω

A (gain) can be big

Generally, huge gain is not needed. $10 < A < 100$ is usually adequate in many applications.

Dirty secret of integrated circuit amps: It is very difficult to have a batch of amplifiers whose parameters are tightly controlled, particularly the gain. For the gain, the tolerance may be 50%!

Contrast this with resistors, where tolerances of 5% are standard and tolerances of 1% are easily (and cheaply) available.

Fight the problem of poor amplifier tolerance with feedback.

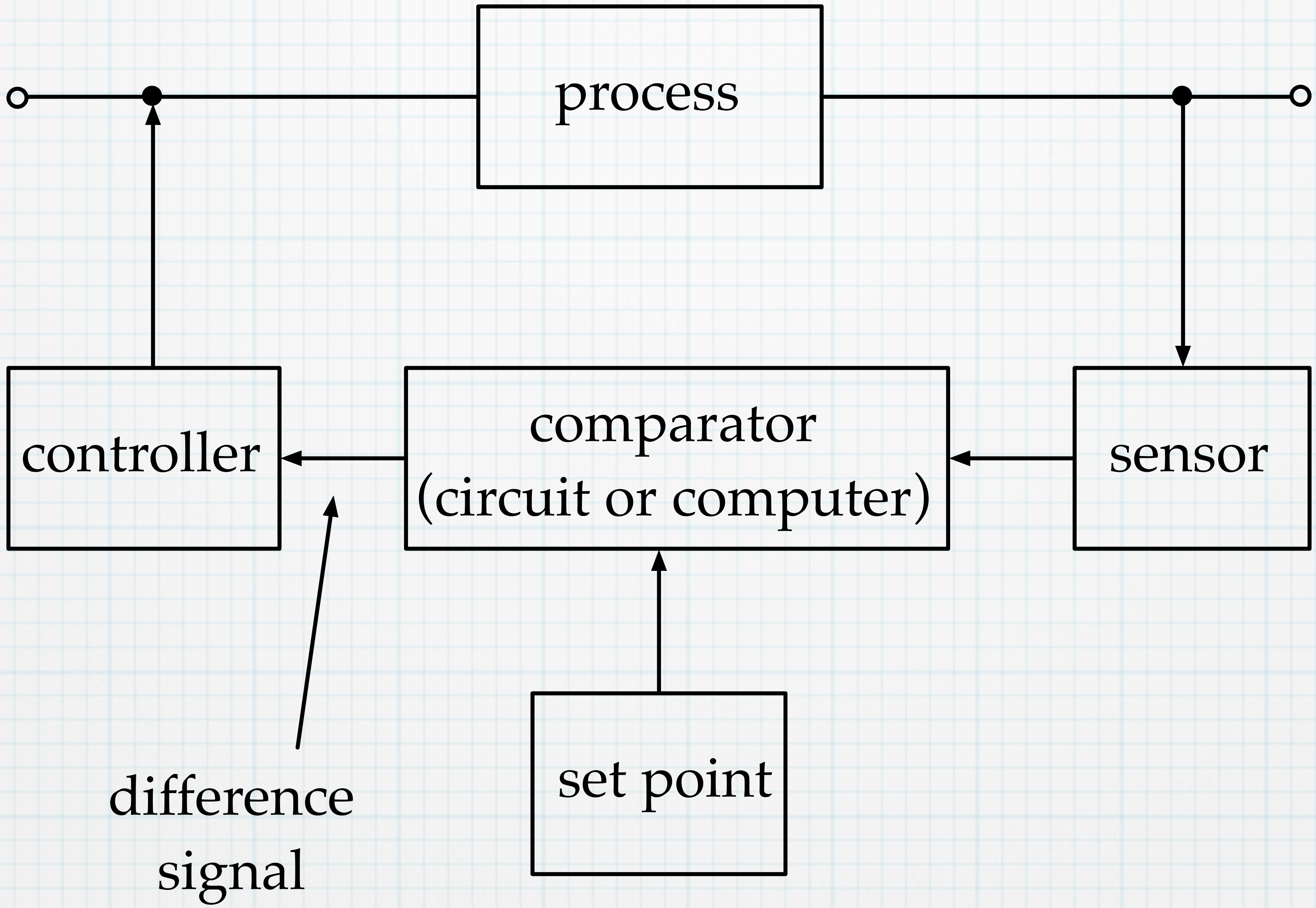
Feedback is the corrective process that allows the controlled operation of all kinds of systems: electrical, mechanical, chemical, even biological.

Much of engineering is geared toward applying feedback control systems to more and more situations.

Examples of feedback control:

- temperature control (furnace/air conditioner)
- cruise control in your car (self-driving cars)
- autopilot in a plane
- robots (particularly manufacturing)
- humans use feedback control all the time (standing, riding a bike, driving a car, etc. etc.)
- evolution

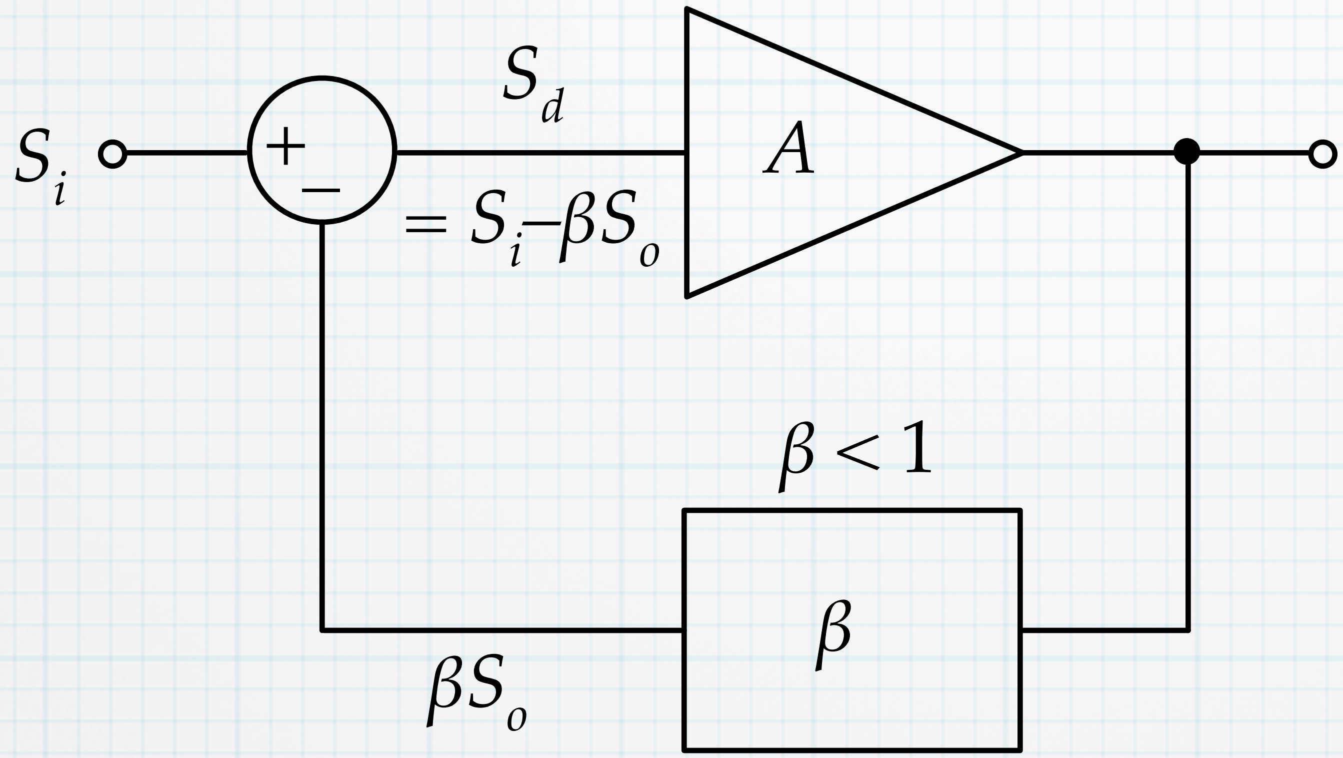
Feedback block diagram



EE 475 & 476. Also, CprE 288 !!

Feedback - applied to an amplifier

System representation – not a circuit diagram!



$S_o = AS_d$

$= A(S_i - \beta S_o)$

$$S_o = \frac{A}{1 + A\beta} S_i$$

$$G = \frac{S_o}{S_i} = \frac{A}{1 + A\beta}$$

Start with an amp – large gain, but not very precise (A = "open-loop" gain)

Sample the output.

Feed back the sample and subtract it from the input – negative feedback. (Closing the loop.)

G is the "closed-loop" gain.

Classic feedback equation.

$$G = \frac{S_o}{S_i} = \frac{A}{1 + A\beta}$$

If A is very large, so that $A\beta >> 1$, then

$$G \approx \frac{1}{\beta}$$

The closed-loop gain has become completely independent of the open-loop gain of the amp and so is free of all the variation that plagues A.

If we can make a very precise feedback loop, with precise β, then we can have a well-controlled gain. Resistors (5% or 1%) can provide for a sufficiently precise feedback loop.

Simple, low-cost amplifier circuits consist of a inexpensive amplifier with very high gain (10^5 to 10^7) together with a feedback loop made up of resistors.

Example

Consider a type of amp that exhibits an absurdly large variation in gain, say from 1000 to 10^5. Use a feedback to try to reduce the variation. Suppose the feedback loop has $\beta = 0.1$ exactly.

$A = 1000$:
$$G = \frac{1000}{1 + (1000)(0.1)} = 9.90$$

$A = 10000$:
$$G = \frac{10000}{1 + (10000)(0.1)} = 9.99$$

$A = 10^5$:
$$G = \frac{10^5}{1 + (10^5)(0.1)} = 9.999$$

With feedback, the variation in closed-loop gain is less than 1%.

Difference signal

It is important to note that the action of the feedback network tends to make the difference signal very small. It is easy to show that

$$S_d = \frac{1}{1 + A\beta} S_i$$

If $A\beta$ is very big, then $S_d \rightarrow 0$.

This means that signal being fed back is almost identical to the incoming signal. The feedback action *forces* this condition to occur. This idea will become the focal point of our analysis of circuits using operational amplifiers, which is our next topic.

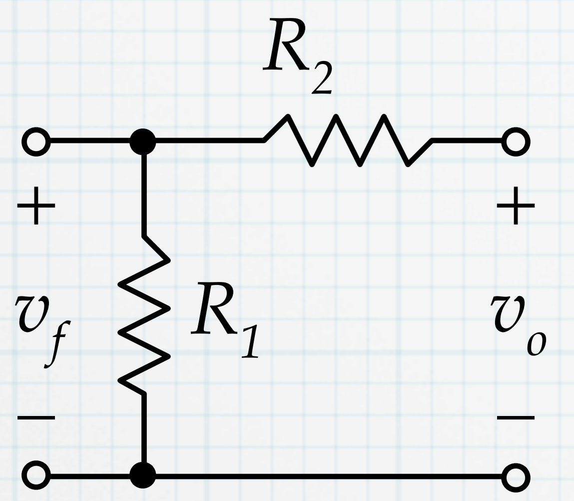
To summarize: We design inexpensive and well-controlled amplifiers by

a. Starting with a high open-loop-gain amplifier ($A > 100{,}000$ is typical).

b. Using a feedback loop to achieve the final (closed-loop) gain.

Feedback circuit

In an amplifier circuit, we feed back the output voltage and subtract it from the incoming voltage signal. (Feeding back the current is also possible, but voltage is more typical.) A commonly used (and simple) feedback is circuit is a voltage divider.



$$v_f = \frac{R_1}{R_1 + R_2} v_o$$

$$= \beta v_o$$

Applying this to an amplifier with a gain of A, the closed loop gain will be:

$$G = \frac{A}{1 + A\beta}$$

$$= \frac{A}{1 + A\left(\frac{R_1}{R_1+R_2}\right)}$$

$$= \frac{R_1 + R_2}{\frac{1}{A}\left(R_1 + R_2\right) + R_1}$$

If A is very big, then $G \approx \frac{R_1 + R_2}{R_1}$

(Upside down voltage divider.)

More details:

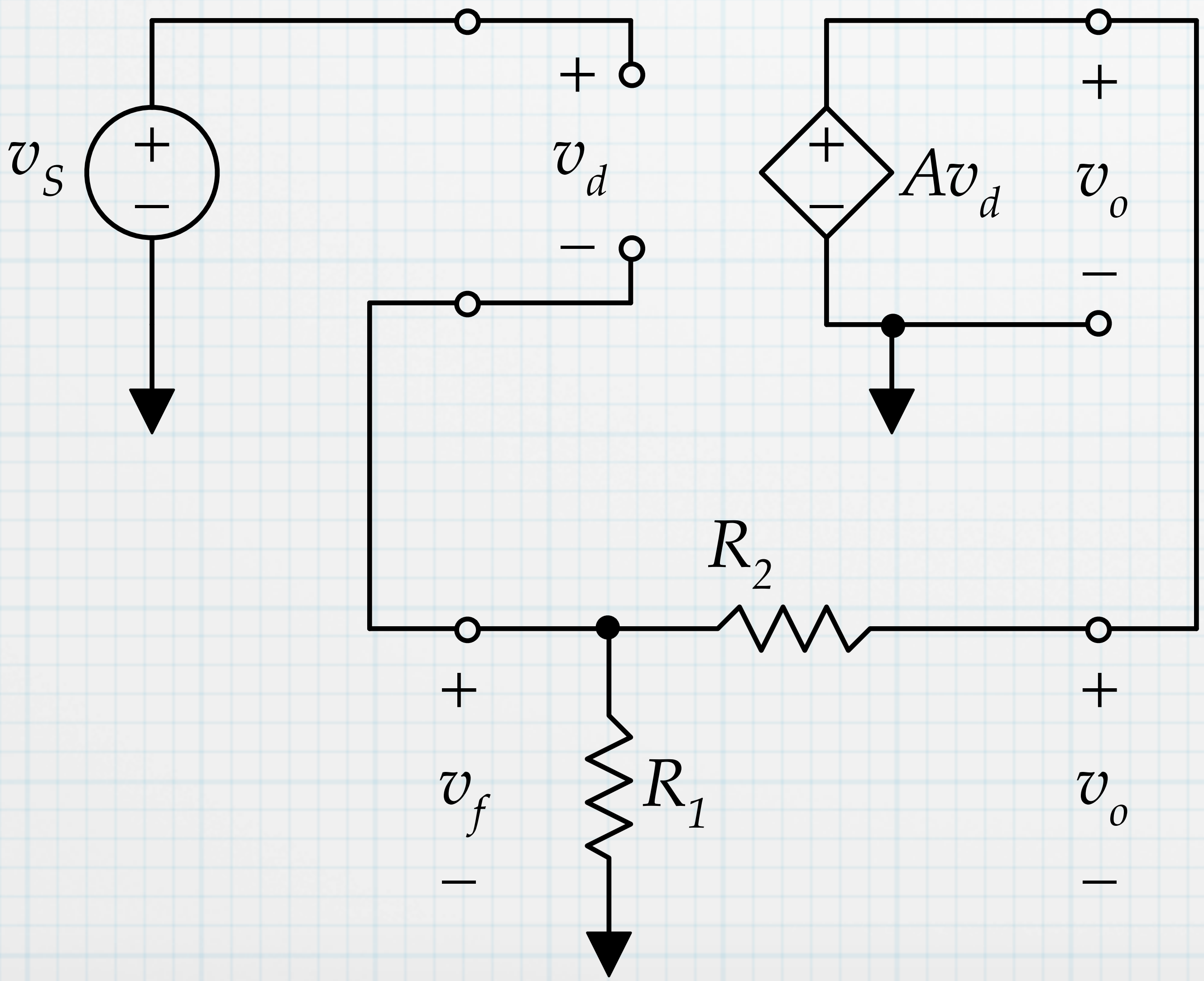
a. Start with an amp. (This one has infinite input resistance and zero output resistance.)

b. Typically, the negative side of the output is at ground. This will be the reference for everything else in the circuit.

c. Add the feedback loop.

d. Tie the feedback loop to the negative terminal of the input.

e. Apply the source voltage to the positive terminal of the input.



v_d is the difference voltage: $v_d = v_S - v_f$.

The amp amplifies the difference voltage, just as we expect in a feedback system.

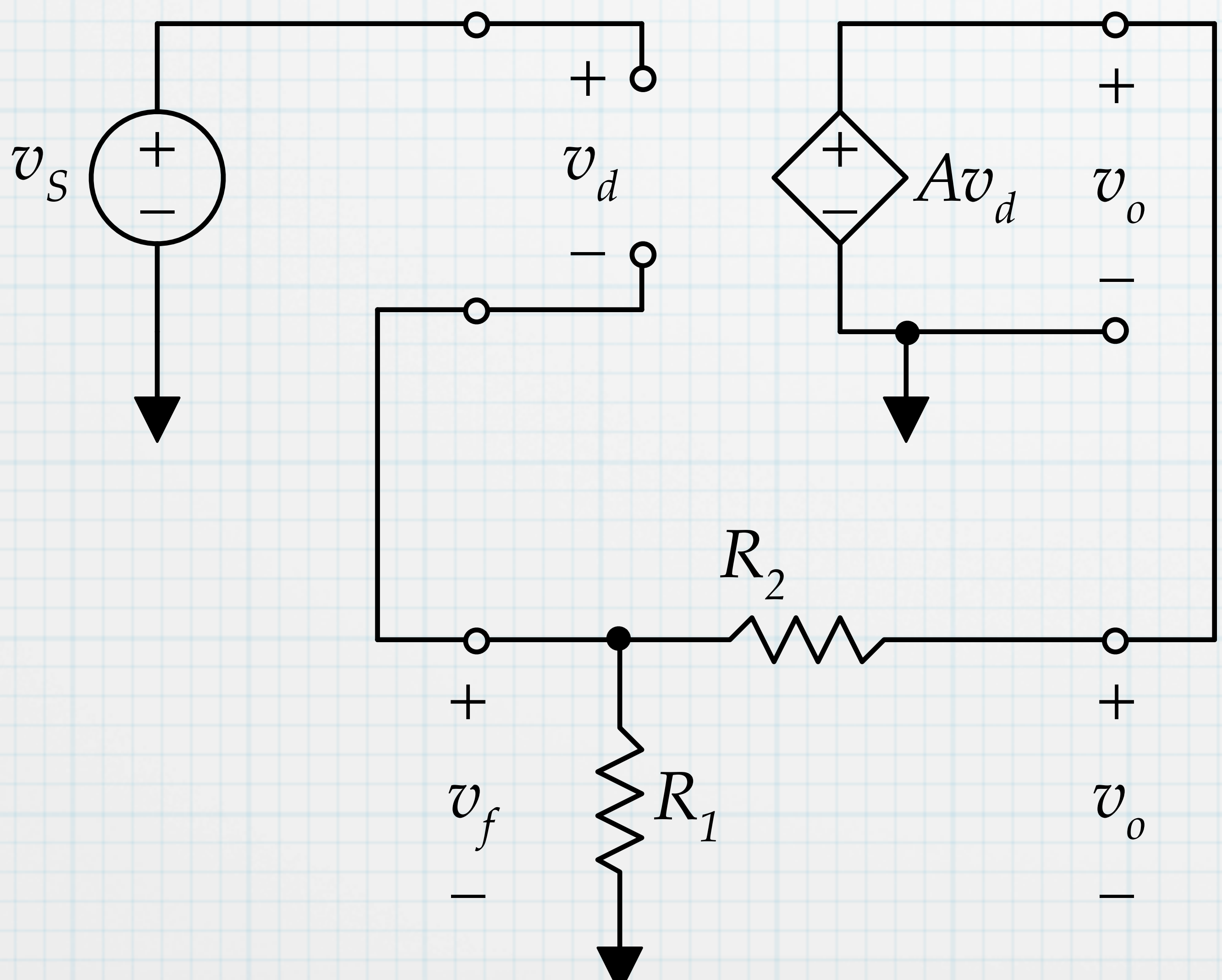
$$v_d = v_S - A\beta v_d$$

$$v_d = \frac{v_S}{1 + A\beta}$$

If A is very big, then, $v_d \approx 0$.

Unfortunately, it is often tricky to apply feedback theory directly to a circuit, because it is difficult to identify the feedback network independently from the amplifier 2-port circuit. If we included input and resistances in the amplifier from the previous example, they would have to somehow be included in the feedback network.

We are saved by the fact that these are just circuits, and we know how to analyze circuits at this point. Forget about trying to identify the feedback part and just apply circuit techniques to find $G = v_o/v_S$.



$$v_o = Av_d$$

$$v_d = V_S - v_f = V_S - v_{R1}$$

$$v_f = v_{R1} = \frac{R_1}{R_1 + R_2} v_o$$

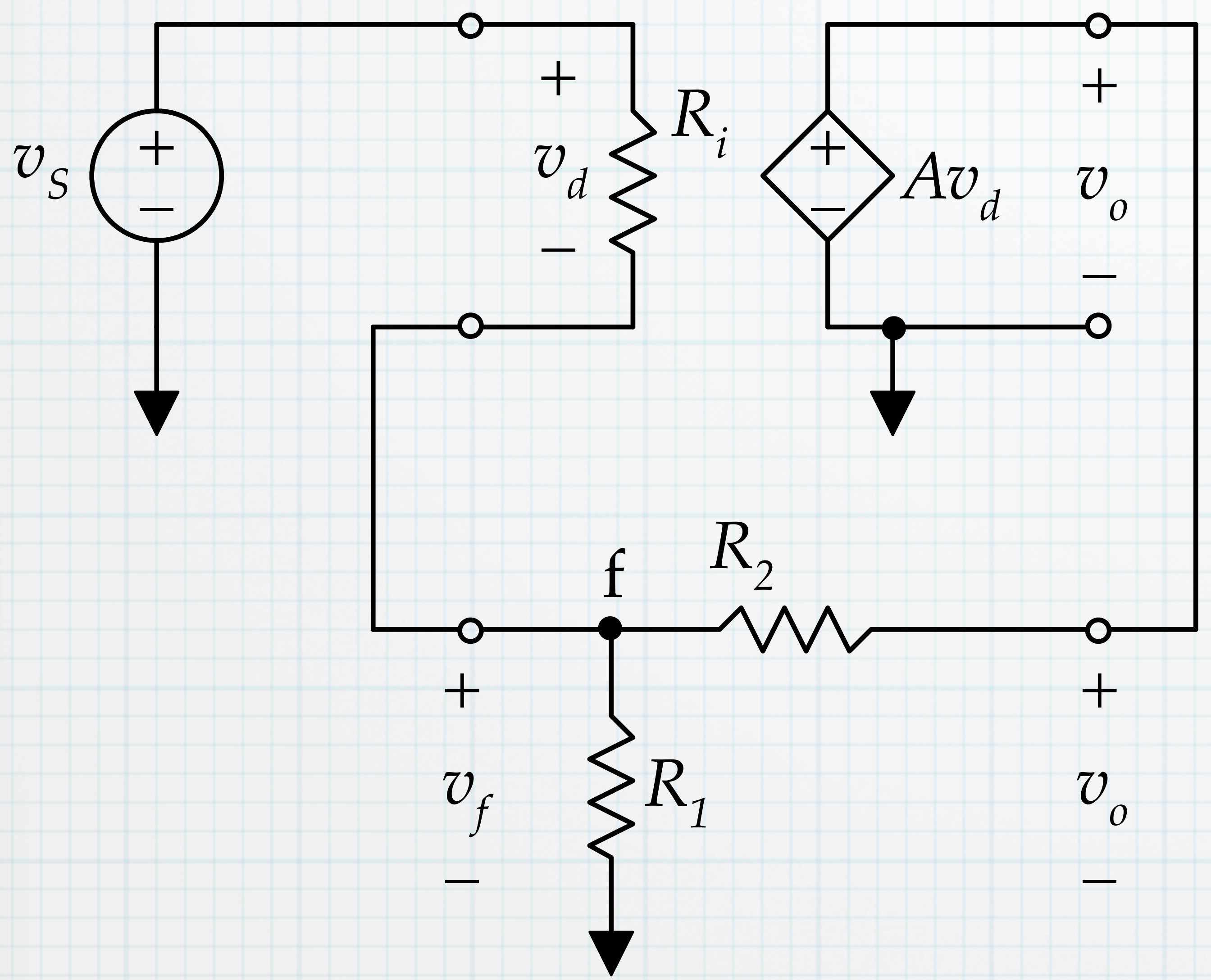
Putting it all together:

$$v_o = \frac{A}{1 + \frac{AR_1}{R_1+R_2}} v_S$$

$$G = \frac{v_o}{v_S} = \frac{R_1 + R_2}{\frac{1}{A}(R_1 + R_2) + R_1}$$

Same as slide 9.

The situation becomes more complicated when the input and output resistances of the amplifier are included. Consider an amp that has a finite input resistance. (Keep $R_o = 0$.)



at node f: $$\frac{v_S - v_f}{R_i} + \frac{v_o - v_f}{R_2} = \frac{v_f}{R_1}$$

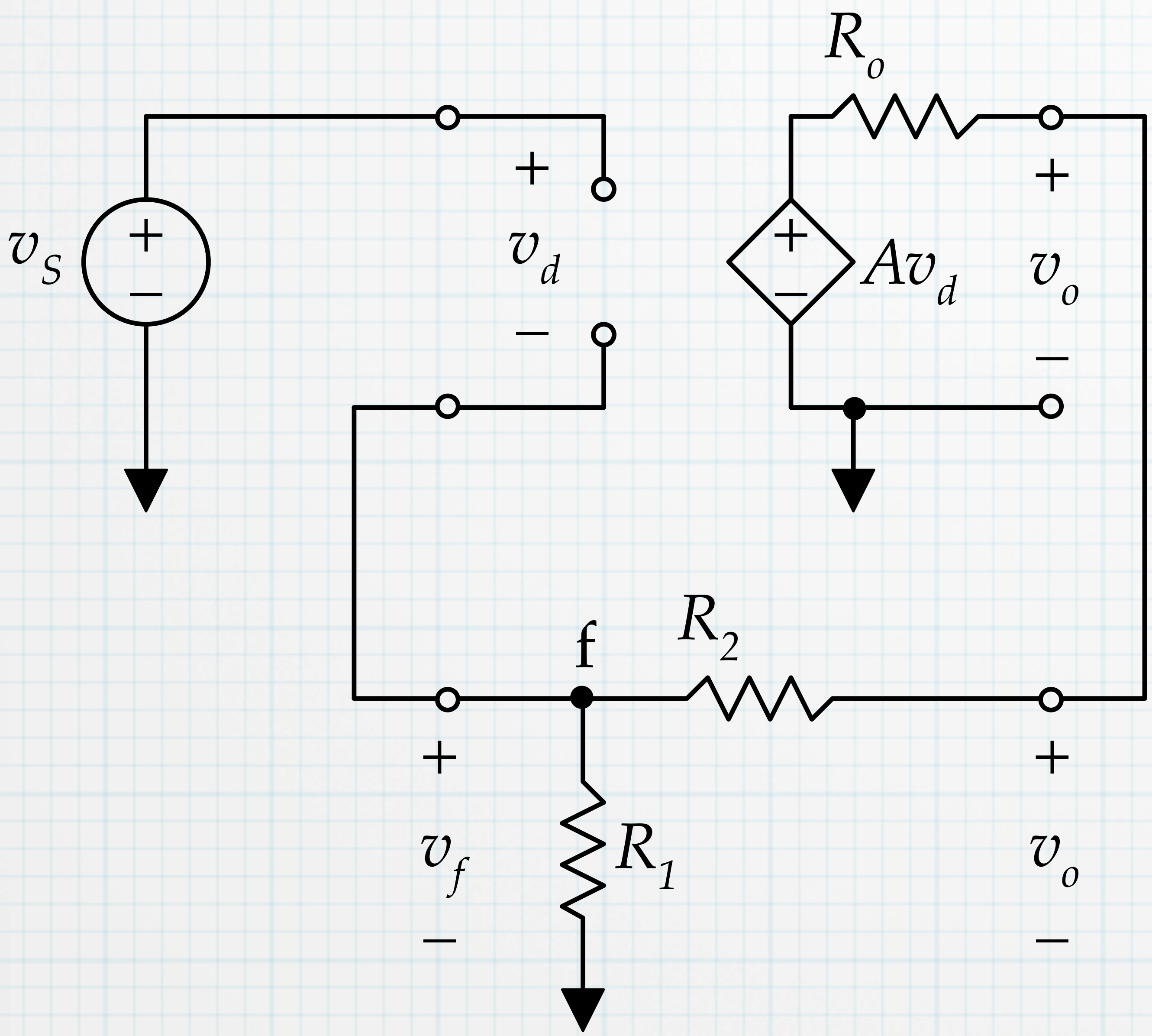
also: $$v_o = Av_d = A\left(v_S - v_f\right)$$

Use the above expressions to eliminate v_f and come up with a single expression that can be manipulated to provide the gain function, $G = v_o/v_S$.

$$G = \frac{v_o}{v_S} = \frac{1 + \frac{R_2}{R_1}}{\frac{1}{A}\left[1 + \frac{R_2}{R_1} + \frac{R_2}{R_i}\right] + 1}$$

Note that this result reduces to the previous result (from slides 9&10) if $R_i \rightarrow \infty$, as we would expect.

Now look at an amp whose two-port model has infinite input resistance, but non-zero output resistance.



$$\frac{Av_d - v_o}{R_o} = \frac{v_o - v_f}{R_2}$$

$$\frac{v_o - v_f}{R_2} = \frac{v_f}{R_1}$$

$$v_d = A(v_S - v_f)$$

Use the above three expressions to eliminate v_f and v_d, and come up with a single expression that can be manipulated to provide the gain function, $G = v_o/v_S$.

$$G = \frac{v_o}{v_S} = \frac{1 + \frac{R_2}{R_1}}{\frac{1}{A}\left[1 + \frac{R_2}{R_1} + \frac{R_o}{R_1}\right] + 1}$$

Note that this result reduces to the previous result (from slides 9 &10) if $R_o \rightarrow 0$.