3 Handouts
Lab 3 (2)
Lecture notes

- Vacuum Tubes, BJT or FET?
- Circuit Analysis: Amplifier & Feedback
- Classic BJT Circuits
- Arduino Intro

Acknowledgements:
Yanni Coroneos, Henry Love
Neamen, Donald: Microelectronics Circuit Analysis and Design, 3rd Edition

Vacuum Tubes

Linear without feedback
Characteristics independent of temperature
Wider dynamic range

- NY Times
  - "Guitar heroes favor vacuum tube amplifiers in their instruments"
  - "Many recording engineers tend to use vacuum-tube equipment in their studios"
  - "Some listeners pay thousands of dollars for high-end tube-based stereo systems and CD players."

BJT or FET

- Depends on application
- Amplifiers
  - BJT
    - are more linear that MOSFET, better fidelity (low harmonic distortion)
    - can drive low impedances at higher power
    - lower noise with low source impedance
    - Operate at < 2 V
  - MOSFET
    - high input impedance
    - Voltage controlled device => lower power

Transistor Configurations

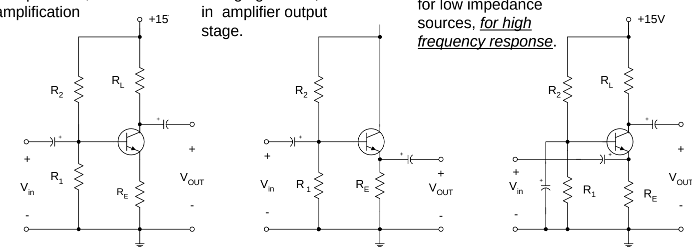
TRANSISTOR AMPLIFIER CONFIGURATIONS

BJT

high input impedance, for general amplification

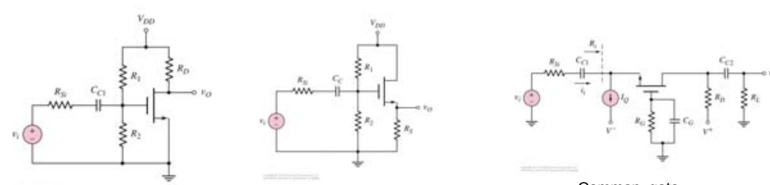
voltage gain = 1 ; use in amplifier output stage.

low input impedance for low impedance sources, *for high frequency response*.



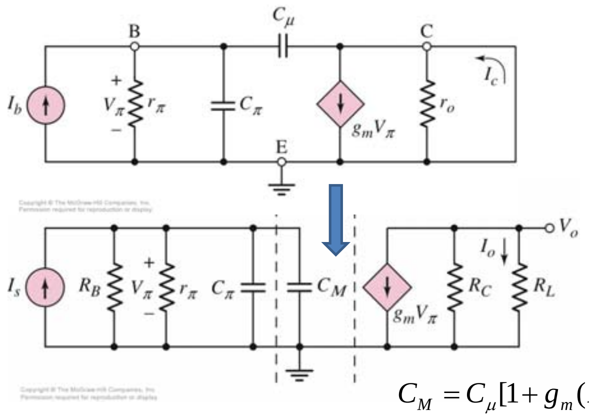
[a] Common Emitter Amplifier [b] Common Collector [Emitter Follower] Amplifier [c] Common Base Amplifier

FET



Common source Common drain [Source follower] Common gate

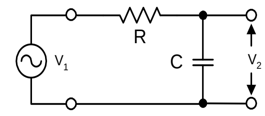
Miller Effect* – Common Emitter



$$C_M = C_\mu[1 + g_m(R_C \| R_L)]$$

* Agarwal & Lang Foundations of Analog & Digital Electronics Circuits p 861

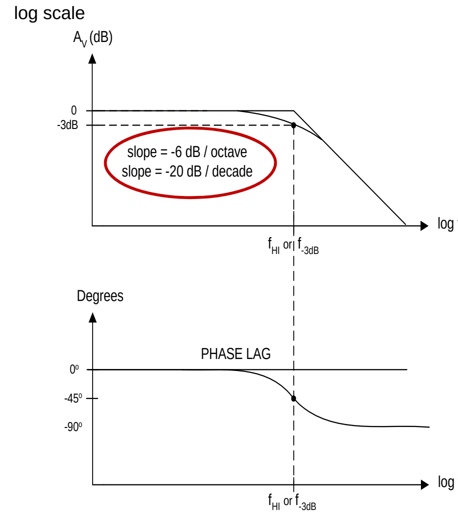
Input Impedance and Frequency Response



$$A_v = \frac{V_2}{V_1} = \frac{j X_C}{R + j X_C} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{j\omega RC + 1}$$

$$A_v = \frac{1}{sRC + 1}$$

$$High\ frequency\ cutoff\ \ f_{hi} = \frac{1}{2\pi RC}$$

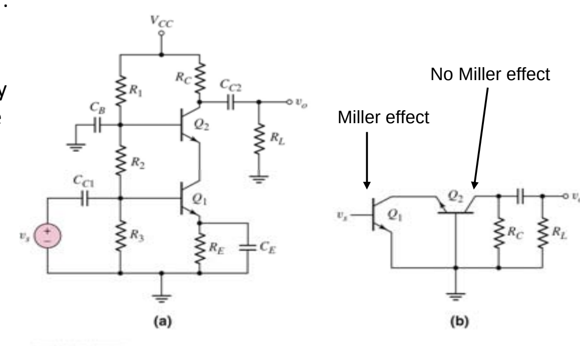


Low Frequency Hybrid-π Equation Chart

Characteristic	Common Emitter	CE with R_E	CC [E. Follower]	Common Base
Voltage Gain [if $r_o >> R_L$]	$A_v = -g_m R_L$	$A_v \approx -\frac{R_L}{R_E}$	$A_v \approx 1$	$A_v = \frac{\beta_o R_L}{r_\pi // R_B + (\beta_o + 1)R_s}$
Current Gain	β_o	β_o	β_o+1	$\frac{\beta_o}{\beta_o + 1}$
Input Impedance	$r_\pi // R_B$	$[r_\pi + (\beta_o + 1)R_E] // R_B$	$[r_\pi + (\beta_o + 1)R_E] // R_B$	$\frac{r_\pi}{\beta_o + 1}$
Output Impedance	R_L [if $r_o >> R_L$]	R_L [if $r_o >> R_L$]	$\left[\frac{(r_\pi + R_s // R_B)}{\beta_o + 1}\right] // R_E$	R_L [if $r_o >> R_L$]
Phase Reversal?	Yes	Yes	No	No
	High gain applications Moderate input resistance High output resistance		Unity gain, low output resistance High input resist.	High gain, better high frequency response Low input resistance

Cascode Amplifer

- Two transistor amplifer: common emitter (CE) with a common base
- Miller effect avoided by setting gain of CE stage low.
- CE stage provides high input impedance
- Common base (CB) provides gain without Miller effect; base is grounded.

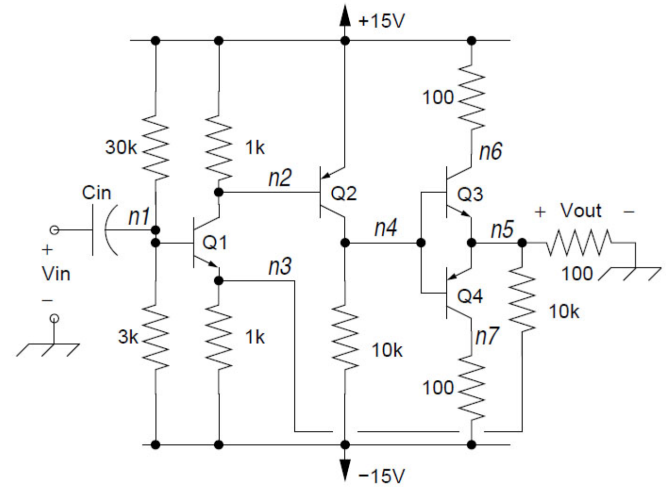


Neamen p445

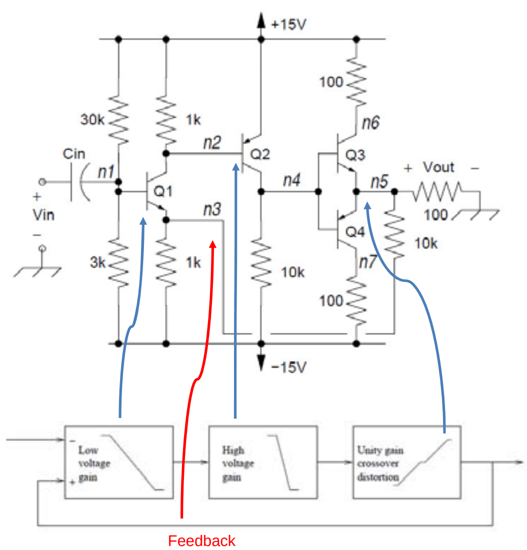
Objectives

- Perform an analysis into the behavior of a complicated circuit using basic properties of BJT's (npn, pnp)
- Calculate gain of the system
- Discuss crossover distortion issues in push-pull amplifiers
- Understand feedback

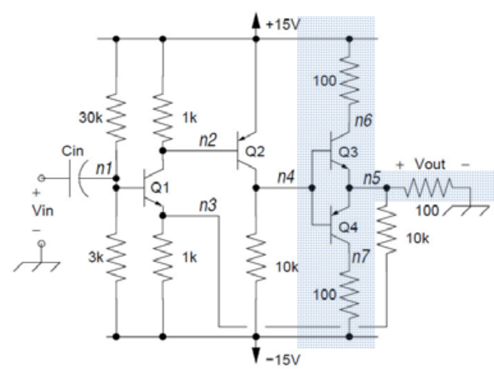
Three Stage – Push Pull Amplifier



Three Stage Amplifer – Block Diagram

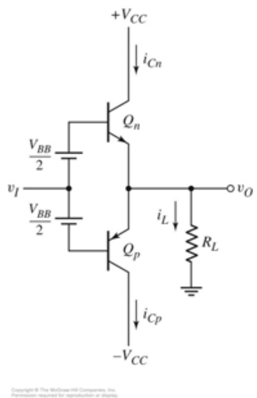


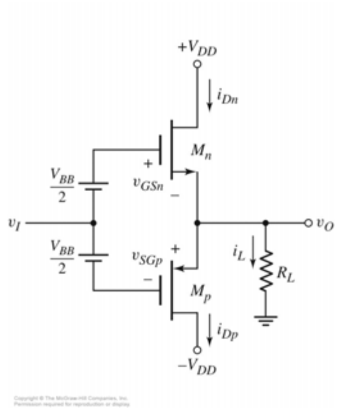
Q3-Q4 Push Pull



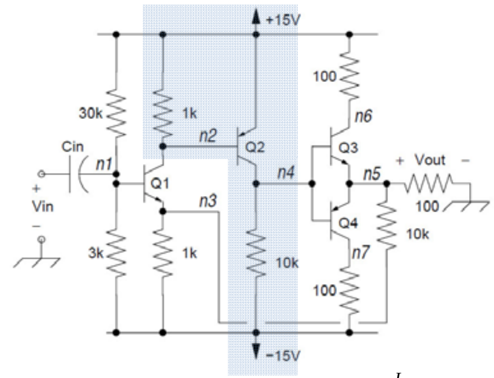
- Q3: Emitter Follower (positve cycle)
- Q4: Emitter Follower (negative cycle)
- Overall gain ~1
- Q3 & Q4 V_{be} are always one diode drop
- Crossover distortion about zero crossing

Crossover Distortion





Q2 – High Gain Stage



- Since last stage is an emitter follower, node n4 should be biased near zero volts.
- Q2 is a common emitter configuration with a pnp transistor.
- For pnp configuration, reverse the polarity of the voltages from a npn.

$$\beta_0 = g_m r_\pi$$

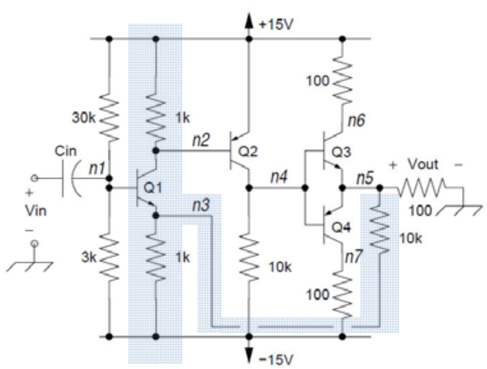
$$g_m = \frac{I_{CQ}}{V_{TH}} \qquad V_{TH} = 26mv$$

$$g_m = \frac{I_{CQ}}{V_{TH}} = 38 * I_{CQ}$$

$$I_{CQ} = \frac{15}{10^4} \quad A_v = -570$$

$$A_v = \frac{-\beta_o R_L}{\frac{\beta_o}{g_m}} = -g_m R_L$$

Q1 Analysis



The emitter follows the base by 0.6v,
v_e incrementally follows v_b

The emitter current $i_E = \frac{v_E - (-15)}{1000} + \frac{v_E - v_{OUT}}{10000}$

The collector voltage, assuming large β ($i_E = i_C$) is $v_C = 15 - 1000 i_C$

Then $\Delta v_C = -\frac{11}{10}\Delta v_B + \frac{1}{10} v_{OUT}$

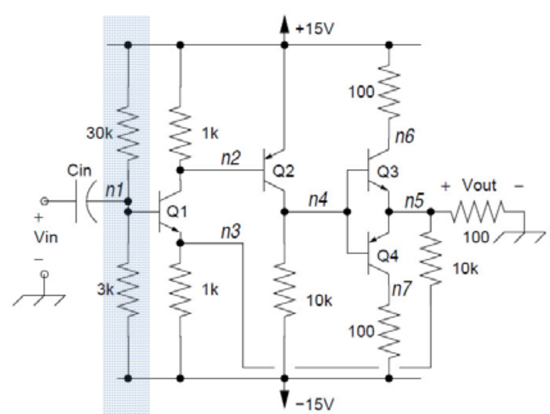
Now we have enough information, i.e. equations to put everything together.

$$v_{OUT} = -570\left(-\frac{11}{10} v_{IN} + \frac{1}{10} v_{OUT}\right)$$

$$v_{OUT}\left(1 + \frac{570}{10}\right) = 570\left(\frac{11}{10}\right) v_{IN}$$

$$\frac{v_{OUT}}{v_{IN}} = \frac{570\left(\frac{11}{10}\right)}{1 + \frac{570}{10}} \approx 10.8$$

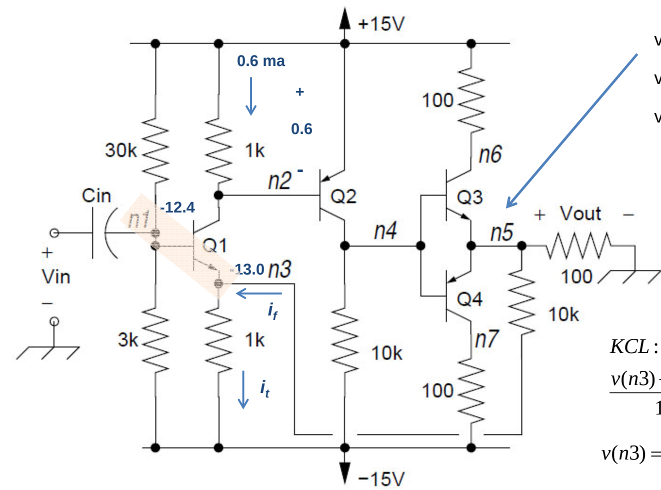
Biasing



Biasing – Quiescent Point

- Determine the quiescent point
- For BJT
  - assume V_{be} = 0.6V
  - assume base current neglible
- Apply KVL, KCL

Biasing – Quiescent Point



v(n5) = Vout = 0

v(n1) - v(n3) = 0.6

v(n2) = 15 – 0.6

$$KCL: \; i_t = 0.6 + i_r$$

$$\frac{v(n3)-(-15)}{1k} = 0.6 + \frac{0-v(n3)}{10k}$$

$$v(n3) = -13 \;\; or \;\; v(n1) = -12.4v$$

$$v(n1) = -12.3v \;\; for\, 30k/3k$$

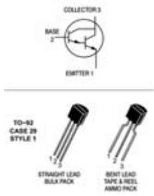
Key Observations

- Crossover distortion caused by base emitter voltage.
- Feedback results in overall gain independent of β
- Biasing not precise, highly dependent on supply voltage (poor supply voltage rejection)

Classic BJT Circuits/components

- Darlington Pair
- Matched transistors
- Short circuit protection
- Currrent mirror
- Schottky diode
- Baker Clamp
- V_{be} multiplier

MPSA13 Darlington



ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector–Emitter Breakdown Voltage (I_C = 100 μAdc, I_B = 0)	$V_{(BR)CES}$	30	–	Vdc
Collector Cutoff Current (V_{CB} = 30 Vdc, I_E = 0)	I_{CBO}	–	100	nAdc
Emitter Cutoff Current (V_{EB} = 10 Vdc, I_C = 0)	I_{EBO}	–	100	nAdc
ON CHARACTERISTICS (Note 1)				
DC Current Gain (I_C = 10 mAdc, V_{CE} = 5.0 Vdc) MPSA13 / MPSA14; (I_C = 100 mAdc, V_{CE} = 5.0 Vdc) MPSA13 / MPSA14	h_{FE}	5,000 / 10,000 / 10,000 / 20,000	– / – / – / –	–
Collector–Emitter Saturation Voltage (I_C = 100 mAdc, I_B = 0.1 mAdc)	$V_{CE(sat)}$	–	1.5	Vdc
Base–Emitter On Voltage (I_C = 100 mAdc, V_{CE} = 5.0 Vdc)	$V_{BE(on)}$	–	2.0	Vdc
SMALL–SIGNAL CHARACTERISTICS				
Current–Gain – Bandwidth Product (Note 2) (I_C = 10 mAdc, V_{CE} = 5.0 Vdc, f = 100 MHz)	f_T	125	–	MHz

1. Pulse Test: Pulse Width ≤ 300 μs; Duty Cycle ≤ 2.0%.
2. $f_T = |h_{fe}| \cdot f_{test}$.

Matched Pair

National Semiconductor

December 1994

LM3045/LM3046/LM3086 Transistor Arrays

General Description

The LM3045, LM3046 and LM3086 each consist of five general purpose silicon NPN transistors on a common monolithic substrate. Two of the transistors are internally connected to form a differentially-connected pair. The transistors are well suited to a wide variety of applications in low power system in the DC through VHF range. They may be used as discrete transistors in conventional circuits however, in addition, they provide the very significant inherent integrated circuit advantages of close electrical and thermal matching. The LM3045 is supplied in a 14-lead cavity dual-in-line package rated for operation over the full military temperature range. The LM3046 and LM3086 are electrically identical to the LM3045 but are supplied in a 14-lead molded dual-in-line package for applications requiring only a limited temperature range.

Features

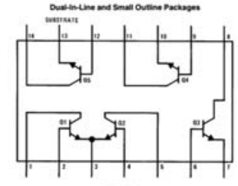
- Two matched pairs of transistors
  V_{BE} matched ±5 mV
  Input offset current 2 μA max at I_C = 1 mA
- Five general purpose monolithic transistors
- Operation from DC to 120 MHz
- Wide operating current range
- Low noise figure 3.2 dB typ at 1 kHz
- Full military temperature range (LM3045) −55°C to +125°C

Applications

- General use in all types of signal processing systems operating anywhere in the frequency range from DC to VHF
- Custom designed differential amplifiers
- Temperature compensated amplifiers

Schematic and Connection Diagram

Dual-In-Line and Small Outline Packages



Top View

Order Number LM3045J, LM3046M, LM3046N or LM3086N
See NS Package Number J14A, M14A or N14A

- Close electrical and thermal characteristics
- Supermatched pairs also available
- Used in differental amplifiers and measurement equipment

Super Matched Pair

LM194/LM394 Supermatch Pair

General Description

The LM194 and LM394 are junction isolated ultra well-matched monolithic NPN transistor pairs with an order of magnitude improvement in matching over conventional transistor pairs. This was accomplished by advanced linear processing and a unique new device structure.

Electrical characteristics of these devices such as drift versus initial offset voltage, noise, and the exponential relationship of base-emitter voltage to collector current closely approach those of a theoretical transistor. Extrinsic emitter and base resistances are much lower than presently available pairs, either monolithic or discrete, giving extremely low noise and theoretical operation over a wide current range. Most parameters are guaranteed over a current range of 1 μA to 1 mA and 0V up to 40V collector-base voltage, ensuring superior performance in nearly all applications.

To guarantee long term stability of matching parameters, internal clamp diodes have been added across the emitter-base junction of each transistor. These prevent degradation due to reverse biased emitter current—the most common cause of field failures in matched devices. The parasitic isolation junction formed by the diodes also clamps the substrate region to the most negative emitter to ensure complete isolation between devices.

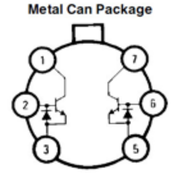
The LM194 and LM394 will provide a considerable improvement in performance in most applications requiring a closely matched transistor pair. In many cases, trimming can be eliminated entirely, improving reliability and decreasing costs. Additionally, the low noise and high gain make this device attractive even where matching is not critical.

The LM194 and LM394/LM394B/LM394C are available in an isolated header 6-lead TO-5 metal can package. The LM394/LM394B/LM394C are available in an 8-pin plastic dual-in-line package. The LM194 is identical to the LM394 except for tighter electrical specifications and wider temperature range.

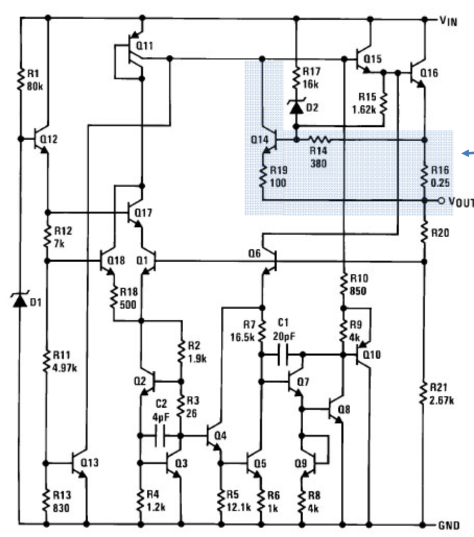
Features

- Emitter-base voltage matched to 50 μV
- Offset voltage drift less than 0.1 μV/°C
- Current gain (h_{FE}) matched to 2%
- Common-mode rejection ratio greater than 120 dB
- Parameters guaranteed over 1 μA to 1 mA collector current
- Extremely low noise
- Superior logging characteristics compared to conventional pairs
- Plug-in replacement for presently available devices

Metal Can Package



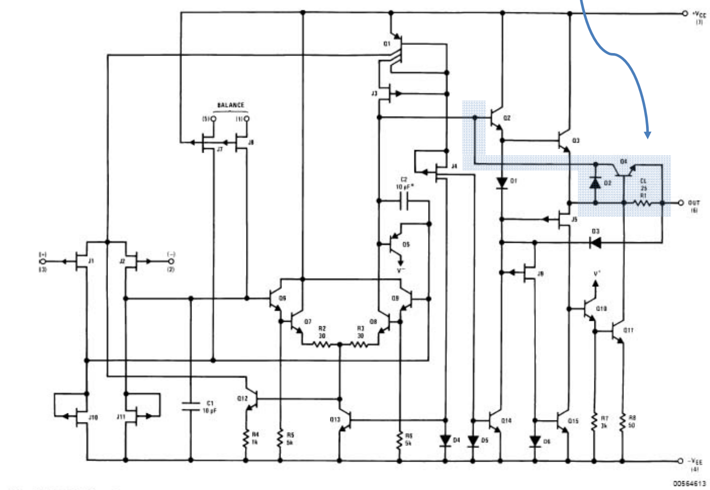
- Characteristics approach theoretical transistor
- V_{be} matched to 50 µv
- h_{FE} matched to 2%



7805 Regulator Short Circuit Protection

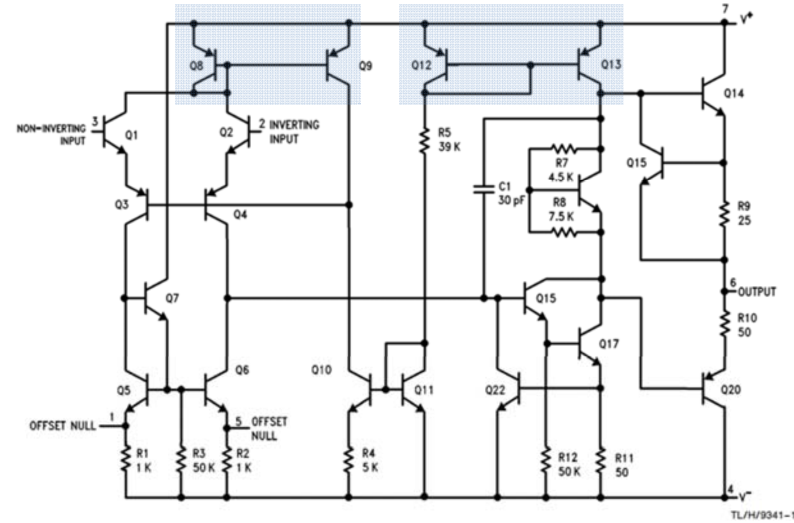
- When voltage across R16 exceeds ~0.6 volt, Q14 diverts away base drive to Q15.
- Note Darlington pair Q15, Q16

356 Op-Amp
Short Circuit Protection

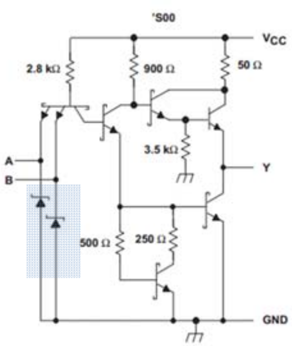


*C = 3pF in LF357 series.

Current Mirror



Schottky* Diode

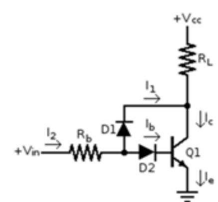


- Schottky diode formed with metal-semiconductor junction vs pn junction
- Lower forward voltage drop: 0.15-0.45 vs 0.6-0.7 for pn junction
- Almost zero reverse recovery times.
- Used in 74LS series logic Low-power Schottky

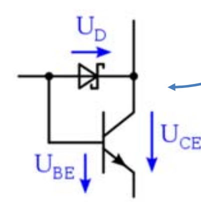
* Walter Schottky

Baker* Clamps

- Reduces turn off time by limiting saturation
- Baker Camp with diodes

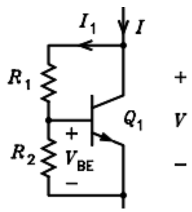


- Baker clamp with Schottky diode



*named by Richard Baker (1956); drawings from http://en.wikipedia.org/wiki/Baker_clamp

V_{be} Multipler



$$V = \frac{(R_1 + R_2)}{R_2} V_{BE}$$

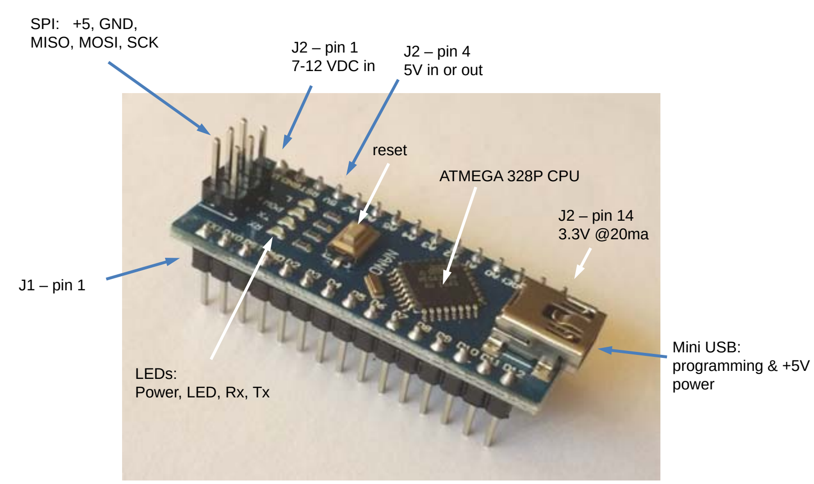
Arduino, Teensyduino

- Low cost open source microcontroller and development system
- Many variants: Uno, Nano, Pro, Teensy ….
- Arduino Nano
  - 16MHz ATmega328, 32KB flash, 1KB EEPROM, 2KB SRAM
  - 22 I/O ports: analog/digital
  - 5V (19ma) operation
- Teensy 3.2
  - 72Mhz MK20DX256, 256KB flash, 2KB EEPROM, 16KB SRAM
  - 34 I/O ports , 21 analog input (2 16bit ADC), 1 12bit DAC
- Ideal for prototyping, process controller or state machines
- Maybe useful for final project but only in a secondary manner:
  - data display, control logic
- Originals vs clones

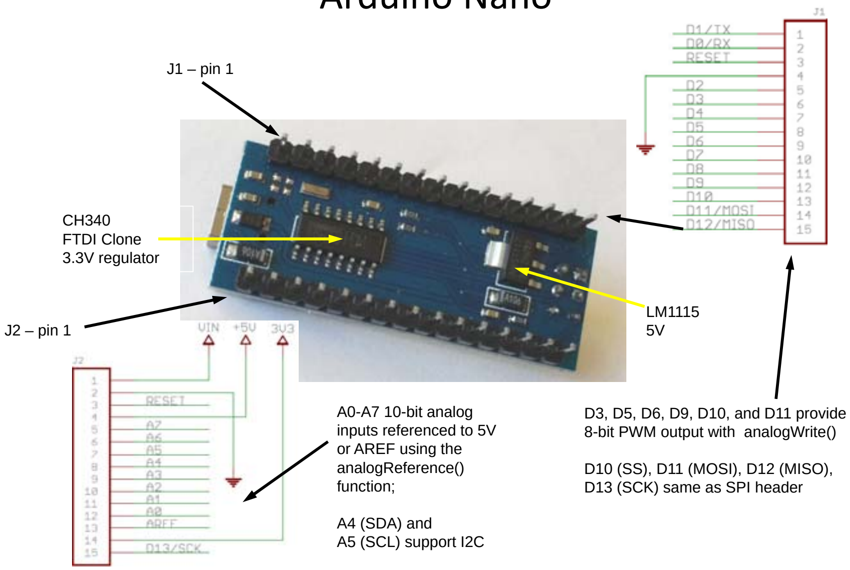
Teensy 3.2 - Nano

	Teensy 3.2	Nano
Processor:	MK20DX256	ATmega328
Clock Speed:	72 MHz	16 Mhz
Flash Memory:	256 KB	1 KB
RAM:	64 KB	2KB
Operating Voltage	3.3 V	3.3 V
GPIO	34	14
Analog Inputs	21	8
DAC	1	0
PWM	12	6
UART	3	external

Arduino Nano



Arduino Nano



Nano Multifunction I/O Pins Partial List

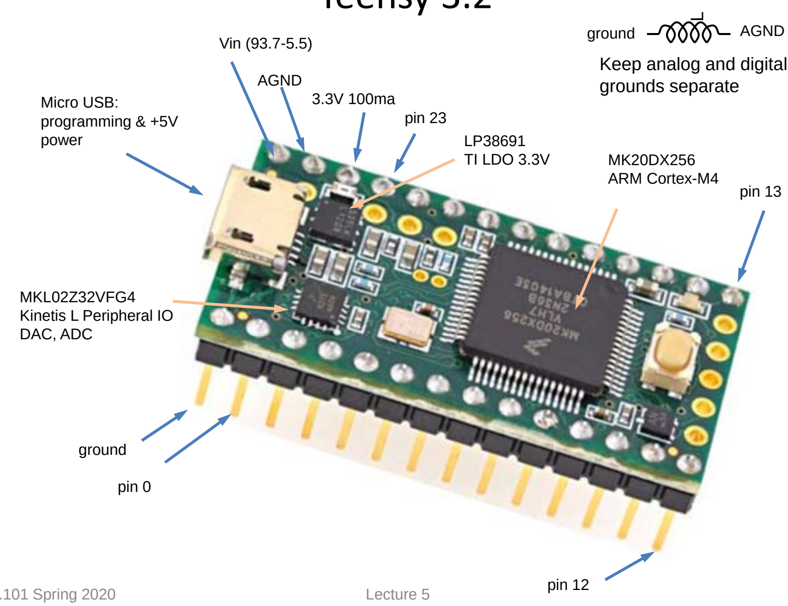
Pin	Function 1	Function 2	Function 3
D13	digital I/O	SCK (SPI)	Built-in LED
D12	digital I/O	MISO	
D11	digital I/O	MOSI	
D3,5,6,9,10,11	digital I/O	PWM	
D3	digital I/O	Interrupt 1	
D2	digital I/O	Interrupt 0	
D1	digital I/O	Tx	
D0	digital I/O	Rx	
A5	analog in	SCL	
A4	analog in	SDA	

Serial Interface

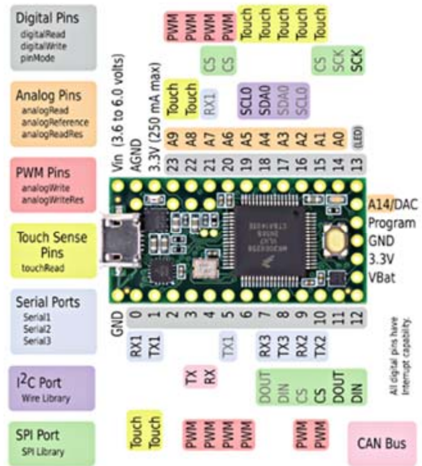
- Arduino Nano clone uses CH340G; need to install serial port driver.
- Drivers on http://web.mit.edu/6.101/www/s2020/drivers/ have been tested.
  - CH341SER_MAC: OSX Mojave
    serial port: cu.wchusbserial1410
  - CH34x_Install_Windows_v3_4.zip: Windows
    serial port: COM3… COMx
  - CH340_LINUX.zip: Ubuntu 14.04
    serial port: /dev/ttyUSB0

```
// driver install
make
sudo make load
```

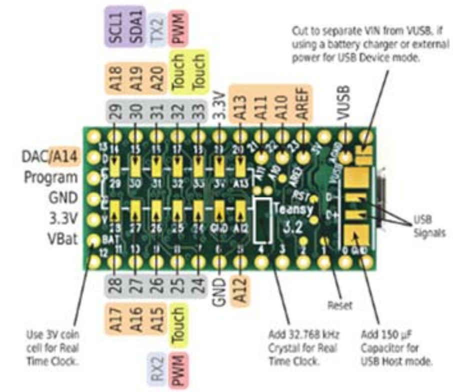

Teensy 3.2



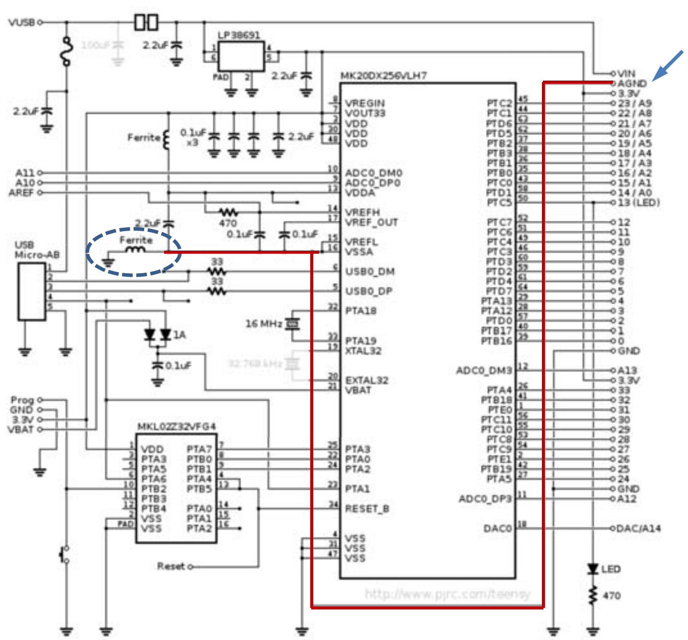
Teensy 3.2 Top



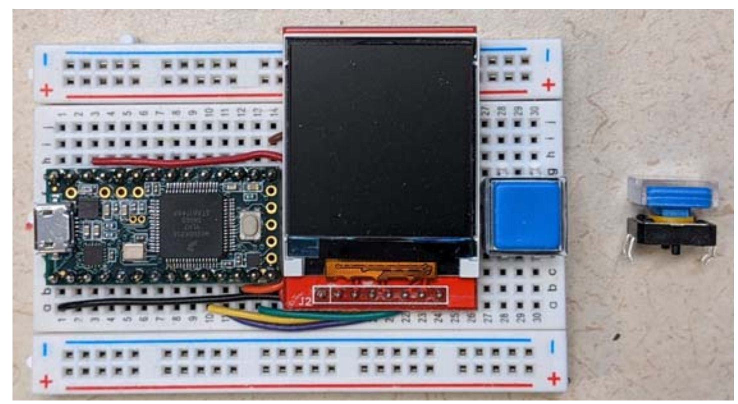
Teensy 3.2 Bottom



Teensy 3.2



Teensy - Lab 3 part 2

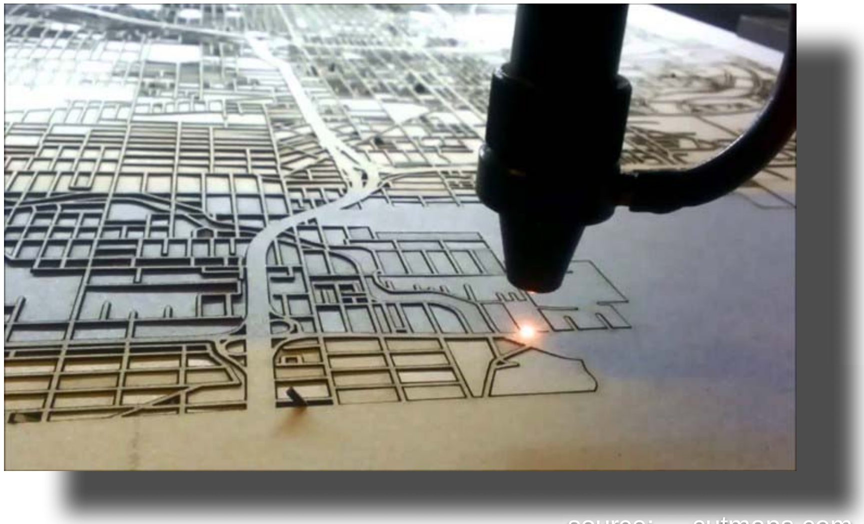


Solder headers to Teensy
Attached spacer to TFT display
Wire circuit

Load sketch & verify display
Circuit will be used in PPG and ECG labs

Laser Cutting

(it's just as cool as it sounds)



source: cutmaps.com

Process

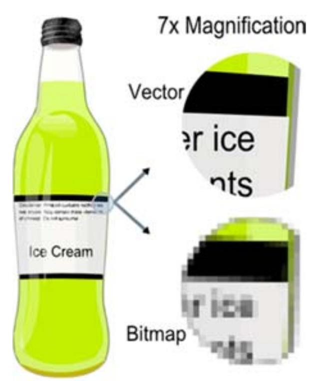
- high-power laser beam optically guided to machine head
- head moves in 2D (x, y)
- beam fired in rapid pulses while head moves
- material is ablated or vaporized
- fumes extracted

source: Universal Laser Systems

source: n-e-r-v-o-u-s.com

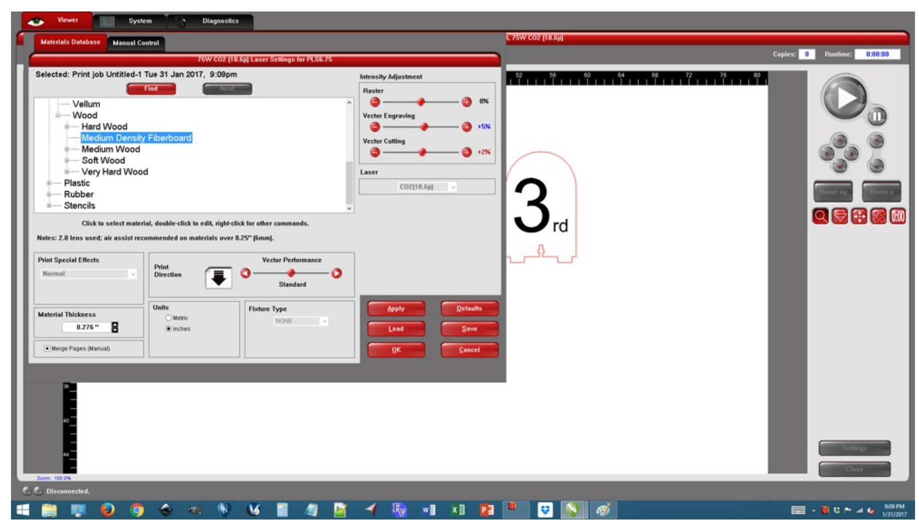
Design

- user generates 2D design
- vector vs. bitmap
- user sets power, speed for each color in file
- machine traces vectors
  - moves in steady line
  - line width < 0.001 inch
  - "hairline"
- or rasters bitmaps
  - sweeps back and forth to fill in

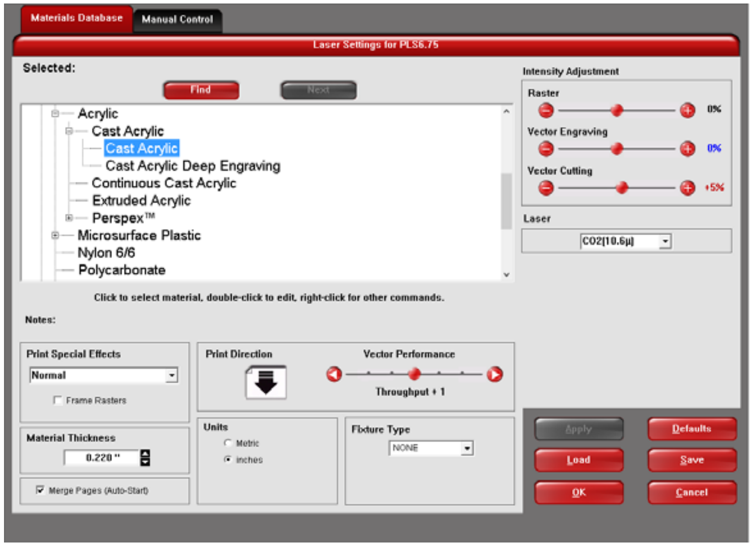


source: wikipedia

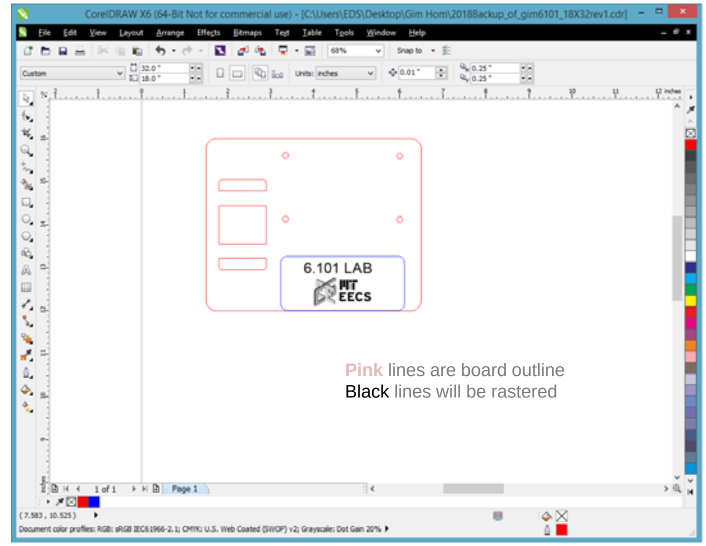
UCP (Universal Control Panel)



Laser "Printing"



Laser Cuting – CorelDraw



Laser Cutting Lab (Optional)

- Mon 2/25 4:15 and 5:15p EDS
- Laser Cut base
- Mount RLC-BJT/MOSFET testor