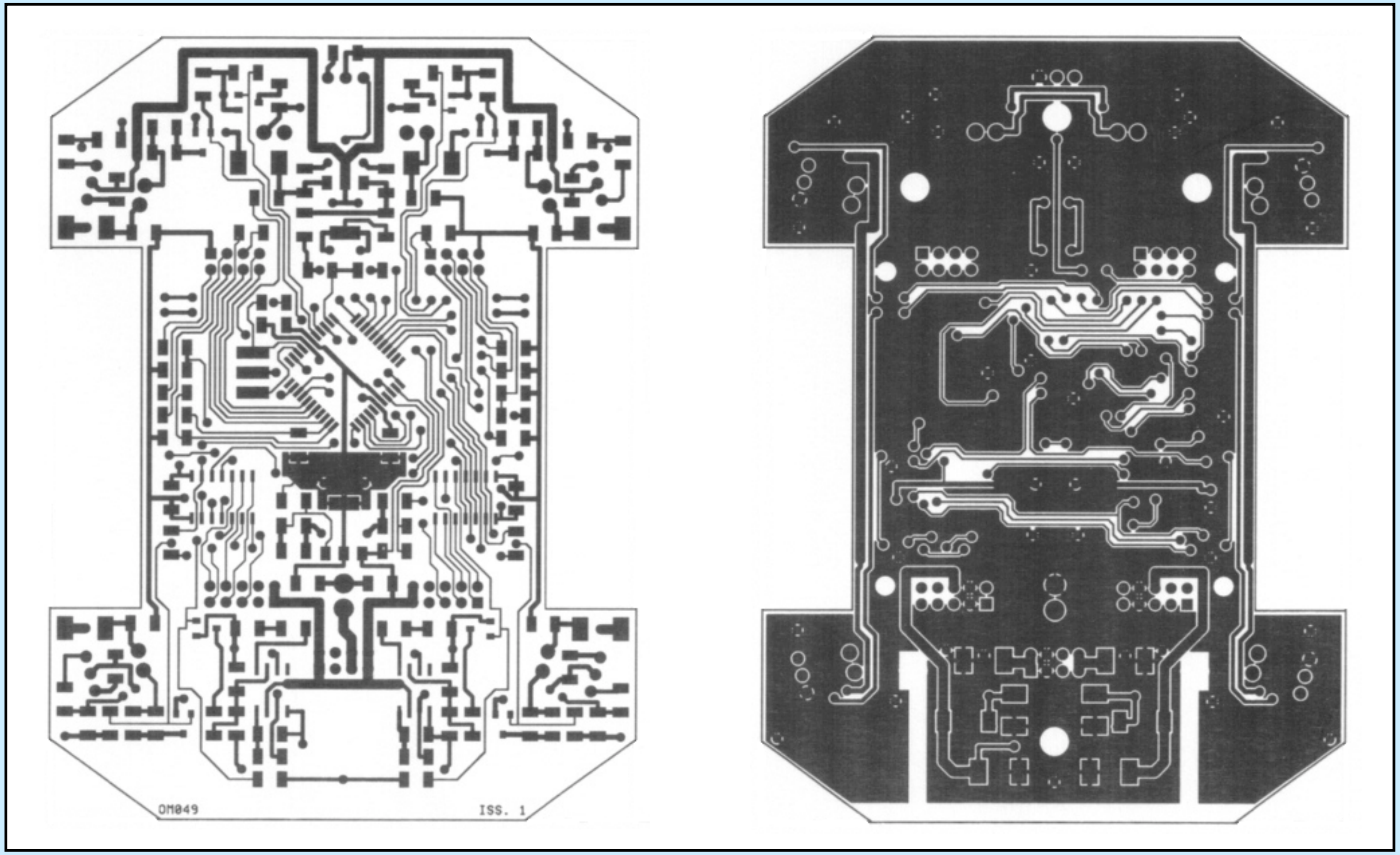
# Power & Ground Systems

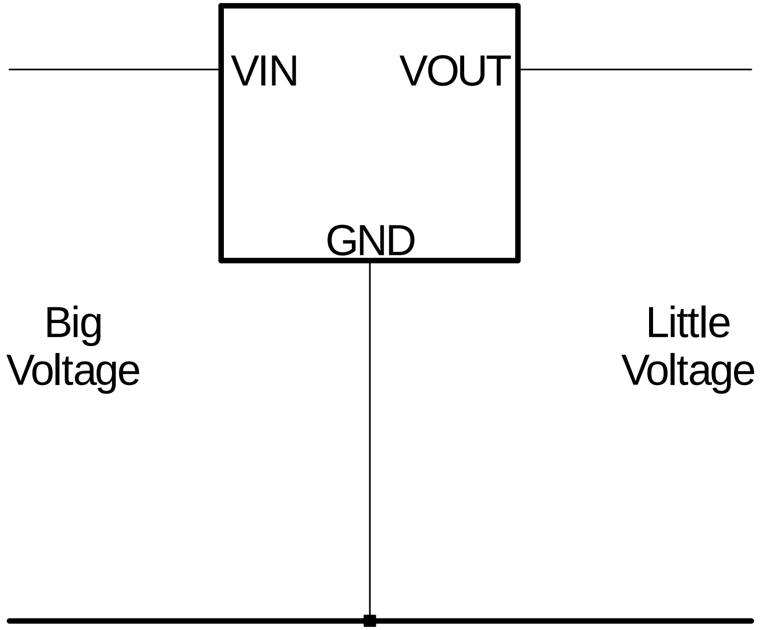



## a few tips on getting it right...er



by Martin Barratt

# Surely - Isn't It Just One of These?




3-Terminal Regulator Circuit

You Might be Right! But Let's See ...

# Introduction

A Good Power and Ground System is essential for:-

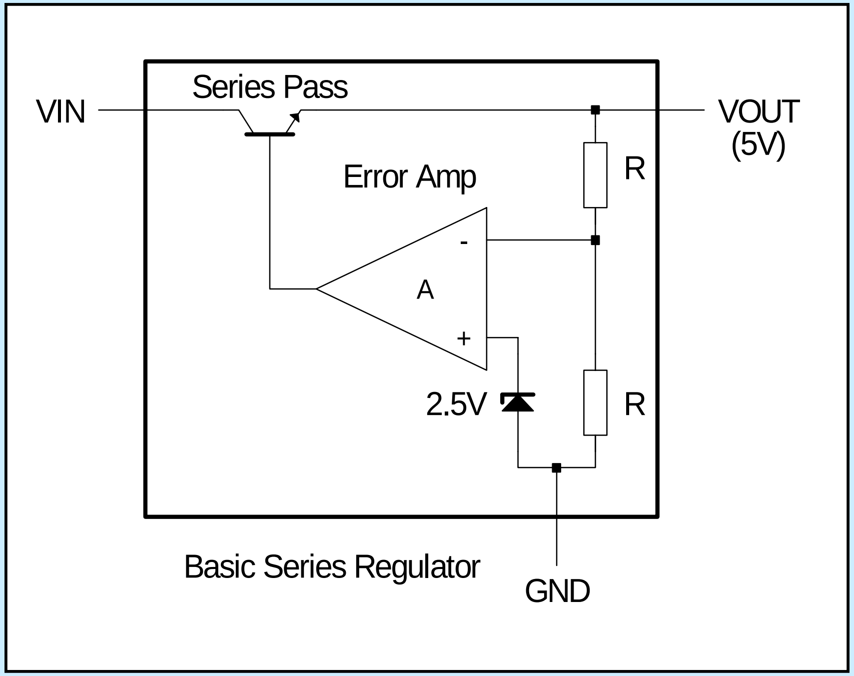
- Circuit Reliability
- Accuracy of Measurements
- Measurement Repeatability
- Low-Noise
- Efficiency

Yet, despite all these benefits, consideration is often only given to this subject once all the ‘interesting’ stuff is complete!

So in the hope of designing better circuits we’ll look at:-

- What Makes a 3-Terminal Regulator Tick
- Useful Devices from a few Popular Families
- Some Regulator Application Considerations
- Some PCB Layout Ideas

# Basic Series Regulator




Simplified Internal Block Diagram of a typical 3-Terminal Regulator

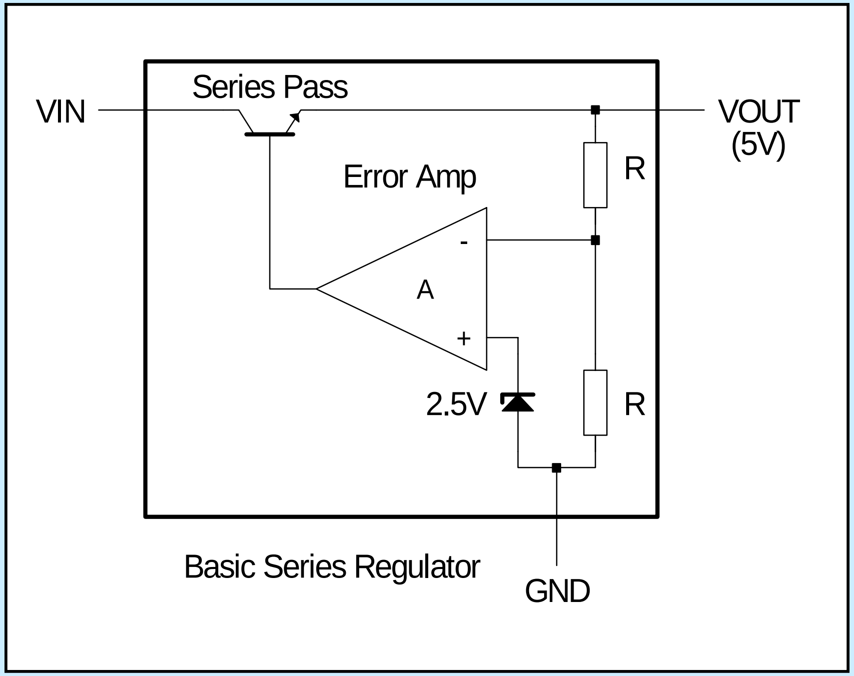
- VIN > VOUT
- Series Pass device does all the hard work
- Error Amplifier compares VOUT with Reference

(Attempts to equalise its Input Voltages)

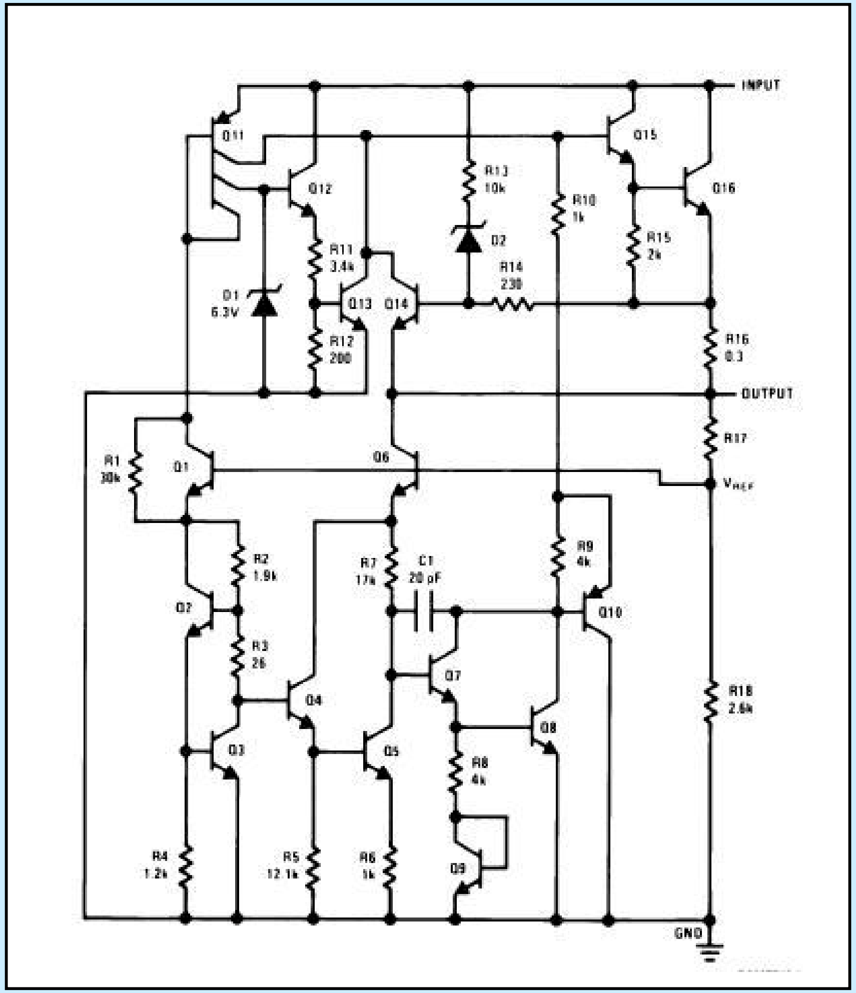
- Ratio of 2 Resistors sets Output Voltage

(If Rs are same value: VOUT = 2 x VREF)

# Basic Series Regulator




- Series Pass Device - Q15/Q16
- Error Amplifier - Q7/Q8/Q10
- Reference Diode - Q7/Q8
- Short Cct Protection - Q14/R16
- Output Voltage Set - R17/R18




LM78xx Family - Internal Circuit

# Useful Regulator Types

## High Power Regulators:- $I_{OUT} > 1A$

- LM78xx Series Fixed Voltage - Standard Drop-Out
- LM317 Adjustable Voltage - Standard Drop-Out
- LM2940 Series Fixed Voltage - Low Drop-Out

All the above are available in various TH and SMD packages

## Low Power Regulators:- $I_{OUT} < 1A$

- LM1117 Series Fixed & Adjustable Voltage - Semi LDO
- LP2980 Series Fixed Voltage - Low Drop-Out

LM1117 available in various TH and SMD packages - LP2980 only in SOT23-5

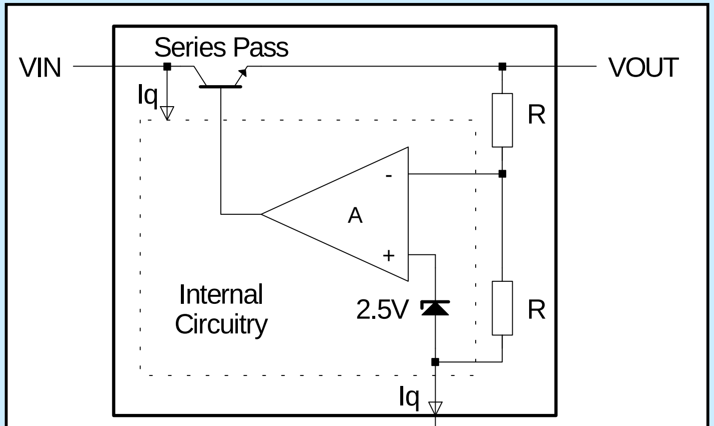
# The LM78xx Family

## Advantages :-

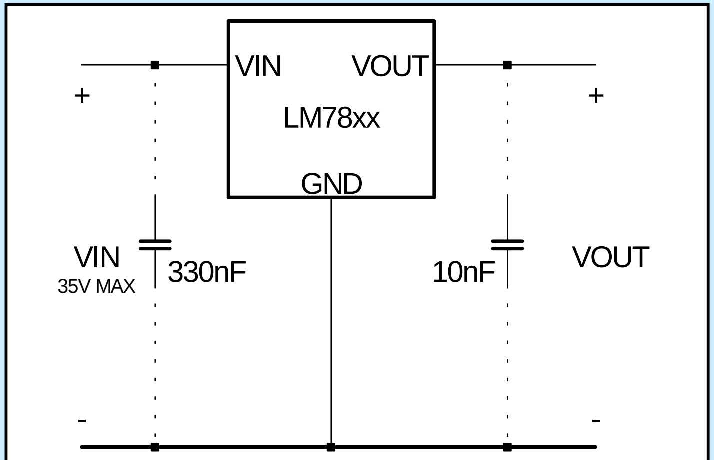
- Very Simple to Use
- Needs 'no' External Components
  - Cin needed if reservoir capacitor is remote - > 50mm
  - Cout reduces high frequency output noise
- Preset Output Voltages (5V, 12V, 15V)
- Available in Negative Output Form - LM79xx
- Available in Low-Power Version - LM78Lxx
- Cheap as Chips

## Disadvantages :-

- Not Low Drop-Out - at least 1.5V
- Output Accuracy not Special at ±4%
- No Adjustable Version
- Significant Quiescent Current - about 8mA
- Quiescent Current flows to Ground - Wasted



LM78xx Series Regulator

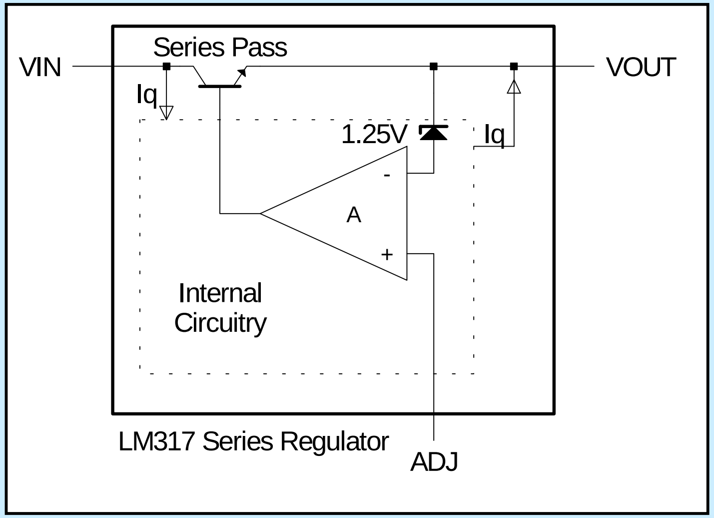


LM78xx Series Application Circuit

# The LM317 Family

## Advantages :-

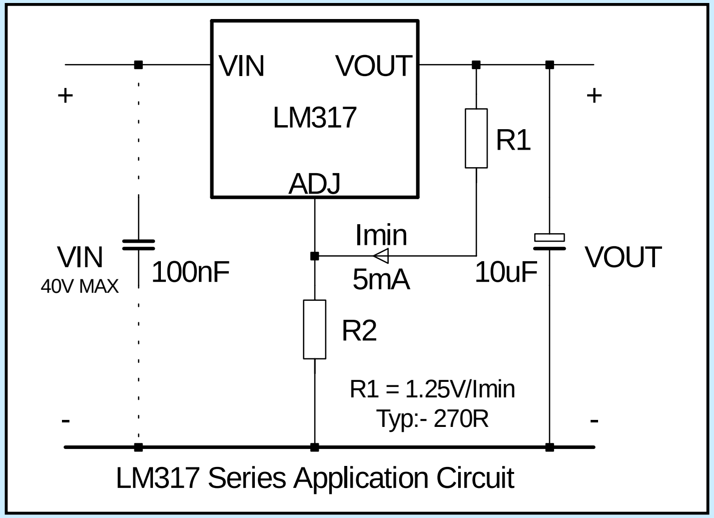
- Simple to Use
- Adjustable Output Voltage - 1.25V to 37V
  - VOUT = 1.25V x (1 + R2/R1) + (IADJ x R2)
  - If IMIN >> IADJ then VOUT = 1.25V x (1 + R2/R1)
- Available in Low-Power Version - LM317L
- Quiescent Current flows to Output Pin
- Low Adjustment Pin (‘GND’) Current - 50uA
- Cheap as Chips



LM317 Series Regulator

## Disadvantages :-

- Not Low Drop-Out - at least 1.5V
- Output Accuracy not Special at ±4%
  - But you can trim it if R2 is made variable
- Needs 2 Resistors to set Output Voltage
- No Negative Output Version



LM317 Series Application Circuit

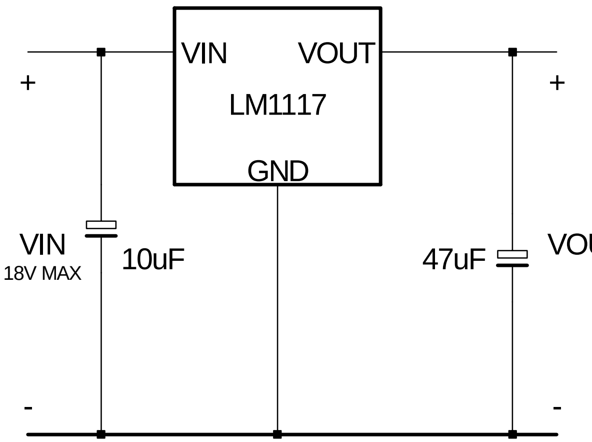
# The LM1117 Family

## Advantages :-

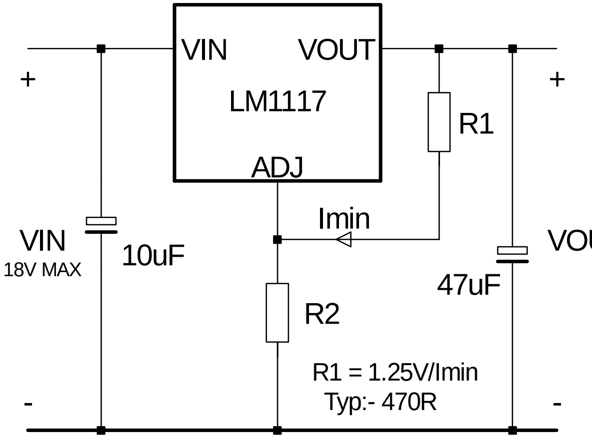
- Simple to Use
- Semi Low Drop-Out Voltage - about 1V
- Available in Fixed and Adjustable Versions
  - Fixed Versions provide 1.8V, 2.5V, 3.3V and 5V
  - Adjustable Version can be set over 1.25V to 14V (VOUT equations same as for LM317)
- Quiescent Current flows to Output Pin
- Output Accuracy not Bad at ±2%

## Disadvantages :-

- Low Maximum Input Voltage - 18V
- Needs 2 Resistors to set Output Voltage
- COUT ESR Specification Tight
- No Negative Output Version



LM1117 Fixed Application Circuit

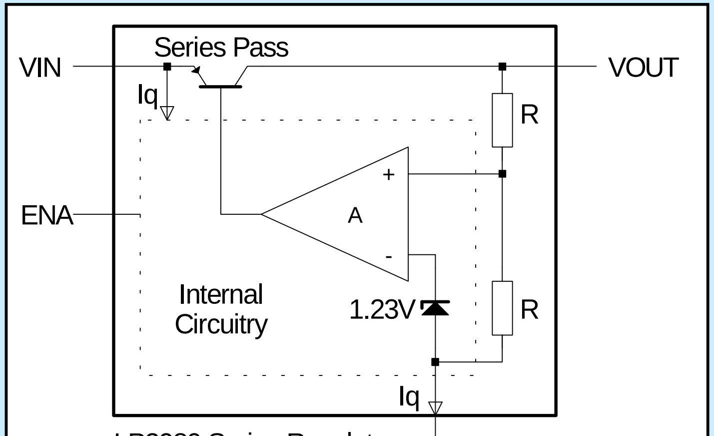


LM1117 Adjustable Application Circuit

# The LP2980 Family

## Advantages :-

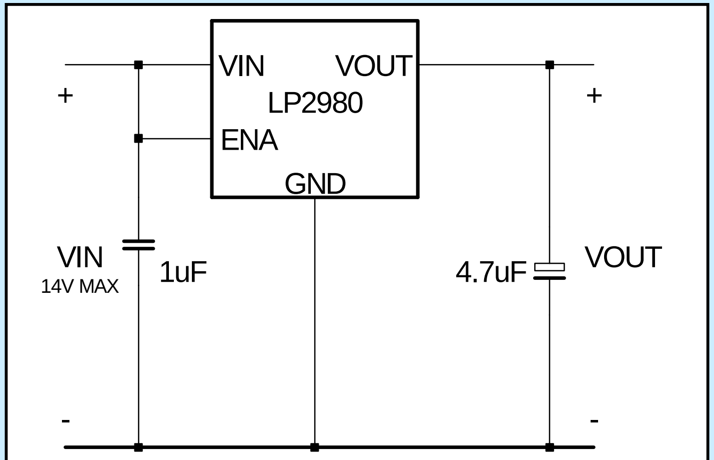
- Simple to Use
- Very Low Drop-Out Voltage - 0.1V @ 50mA
- Preset Output Voltages (3.0V, 3.3V, 5.0V)
- Low Quiescent Current - flows to GND Pin
- Output Accuracy not Bad at ±1.5%
- Fast Transient Response
- Shutdown Capability
- Small Size - SOT23-5 Package



LP2980 Series Regulator

## Disadvantages :-

- Low Maximum Input Voltage - 14V
- COUT ESR Specification Tight
- Only Suitable for Low Current Use <50mA



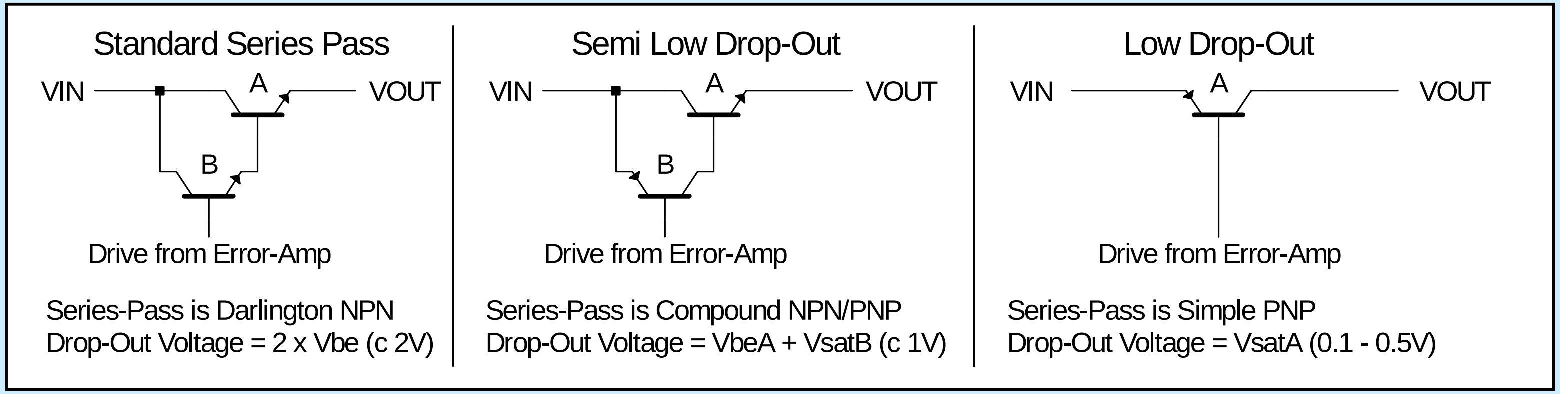
LP2980 Application Circuit

# Voltage Regulator Considerations

Using 3-Terminal Regulators is not always Straightforward. Problem Areas Can be:-

- Drop-Out Voltage
- Minimum Load Current
- Load Regulation
- Transient Response
- Output Capacitor ESR on LDOs
- Ground Current
- Thermal Management

# Regulator Drop-out Voltage



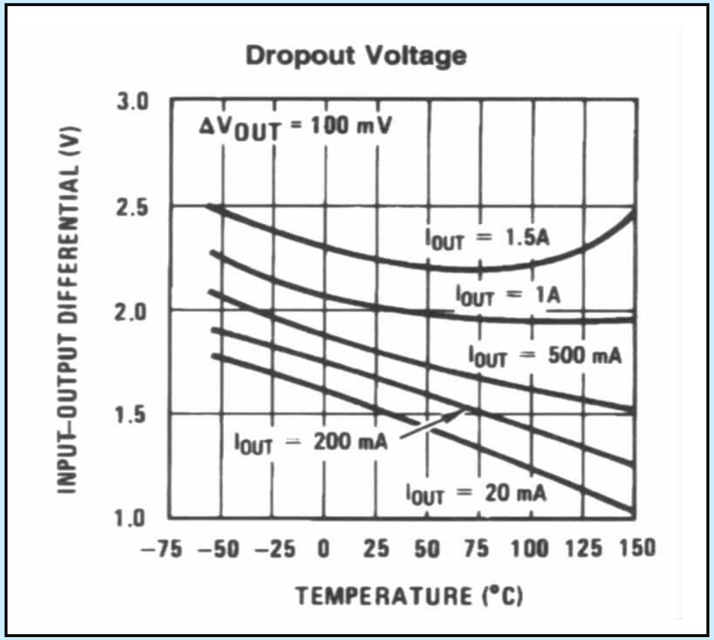

## Standard Series Pass

- High Gain - Low Drive Current
- Driver Current (B) flows to Output
- Lowest ‘Ground Current’ (< 10mA)
- Highest Drop-Out Voltage - up to 2.5V
- Highest Minimum Power Dissipation
- Relaxed De-coupling Requirements
- Lowest Cost

## Low Drop-Out

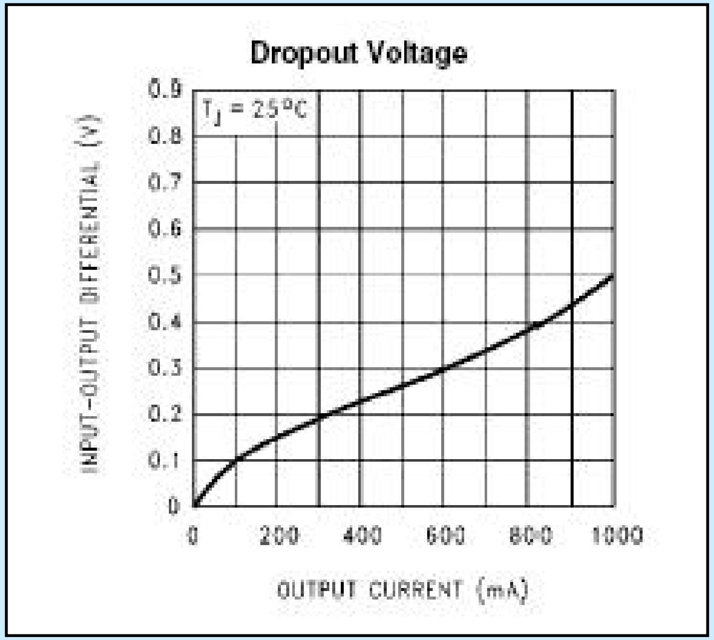
- Low Gain - High Drive Current
- Driver Current (A) flows to Ground
- Highest ‘Ground Current’ (up to 50mA)
- Lowest Drop-Out Voltage - maybe 50mV
- Lowest Minimum Power Dissipation
- Strict De-coupling Requirements
- Highest Cost

# Regulator Drop-out Voltage




Standard Regulator - LM317

$V_{DO}$ @ 0.5A = 1.75V (25°C)




Low Drop-Out Regulator - LM2940

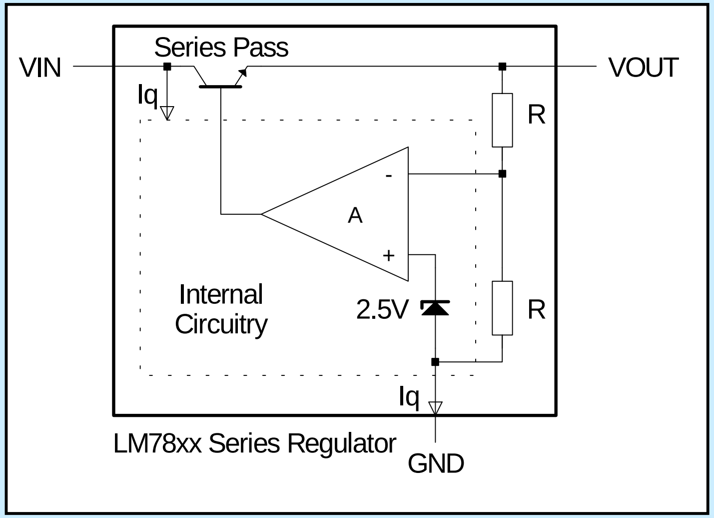
$V_{DO}$ @ 0.5A = 0.25V (25°C)

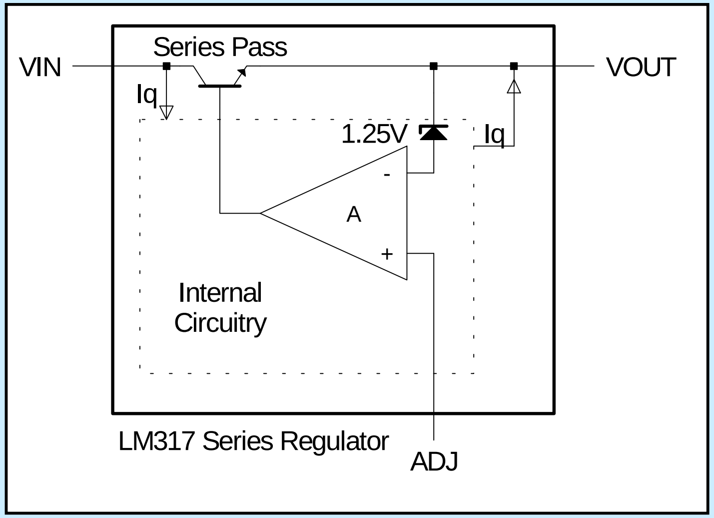
Note that Drop-Out Voltage is typically specified at '*d* Vout' 100mV
Regulator Output will begin to fall from its Nominal Value at a larger Input-Output Differential than indicated on the Graphs

# Minimum Load Current

- Not a Problem with Regulators that 'waste' their Iq to Ground

- For Regulators that return Iq to VOUT we MUST provide a Load
  - it's got to go somewhere!
  - without an adequate 'sink' VOUT will rise above the set output voltage




## So why use this Type?

- Adjustable Output is useful for Odd VOUT
- We can make a small efficiency saving

# Minimum Load Current

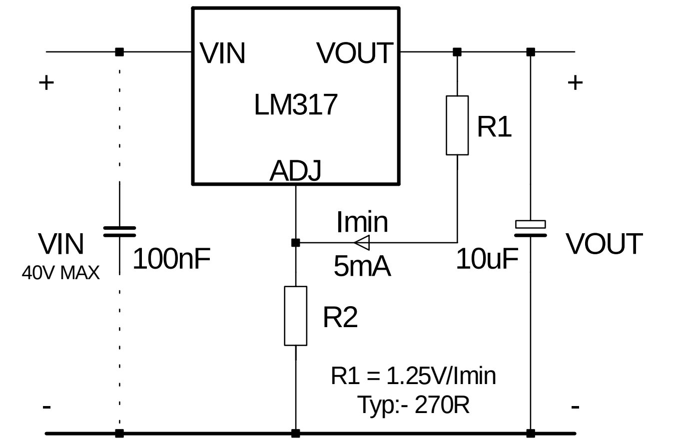
- Standard Application wastes Iq to GND
  - No real benefit over LM78xx
- Hi-efficiency Circuit wastes only 1mA
  - Needs a Minimum Load-Circuit Current

    ILOAD MUST ALWAYS be at least 4mA
  - Not a problem in most Mouse circuits

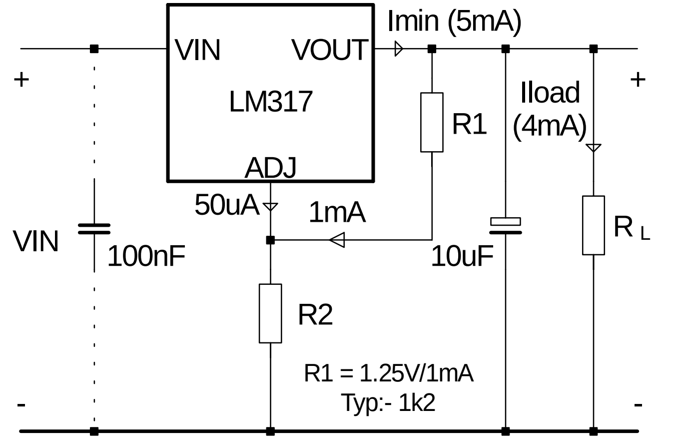
    Microprocessor, Logic ICs and General Circuitry
  - Has an easy approximate VOUT calculation

    VOUT = 1.25V + R2mV - (R2 value in ohms)

Note: if ILOAD can fall below 4mA then increase IR1



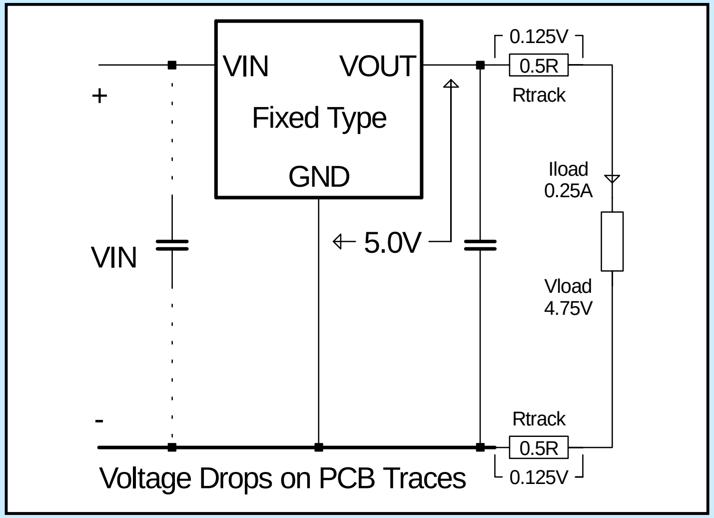

LM317 Series Application Circuit




LM317 High Efficiency Circuit

# Load Regulation

- Regulators define VOUT at Output
  Fixed Output Types:- VOUT to GND
  Adjustable Types:- VOUT to 'R2 -ve' (0V)
- PCB Traces can cause Volt-Drops due to their Resistance
- Even at Modest Load Currents the Drops can be significant:-
  Combination of 2 x 0.5R Track Resistance and 0.25A Load Current reduces effective supply voltage by 0.25V
- This is enough to cause Trouble!



# Load Regulation

## Reducing PCB Voltage Drops:-

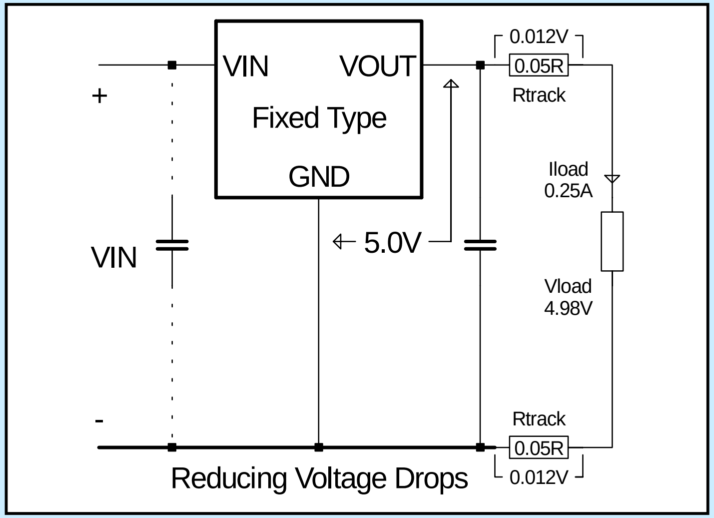
- Method 1

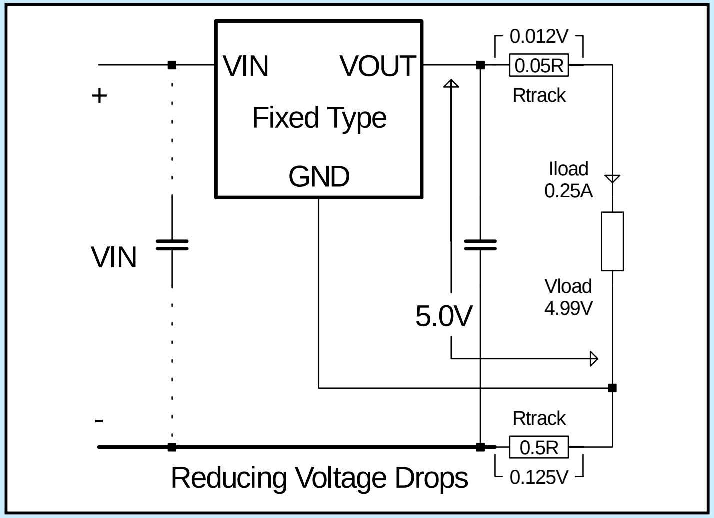
  Reduce Track Lengths from VReg. to Load
- Method 2

  Maximise Track Widths - Reduces ohms/inch
- Method 3

  Return Regulator GND Connection direct to the Load GND Connection

  NOTE: only compensates for drops in the 0V line



# Line Transient Response

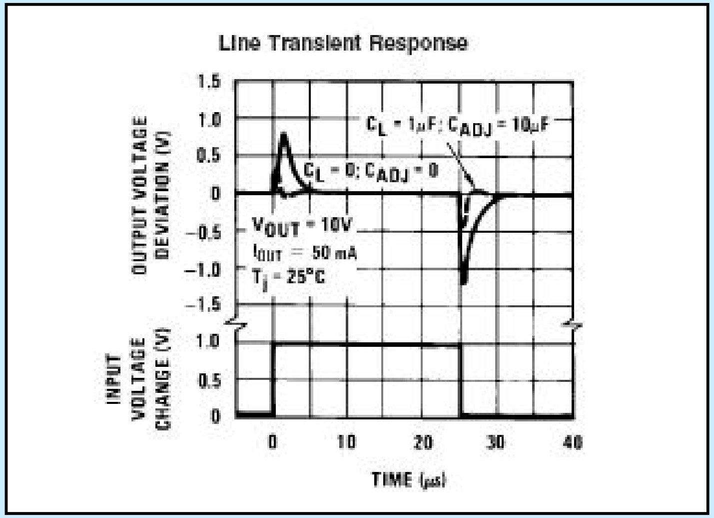
- Line Transients

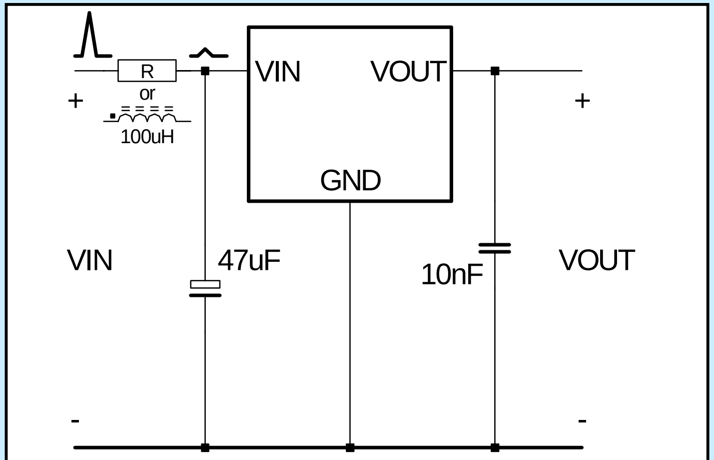
  Change of VOUT if VIN changes suddenly
  Regulator unable to cancel Fast Edges & HF
  Line Transients can be caused by Back-EMF
  Feeds through Regulator to CPU Supply
  - sometimes with little, if any, attenuation
  - mild cases could cause random ADC Conversion errors
  - a bad case could lead to CPU brown-outs

- Possible Solutions

  Choose a Regulator with a better Spec.
  - the LM317 shown is not good in this respect
  - the LM1117 is somewhat better

  Fit Tantalum Capacitors to Input and Output
  Reduce the Amplitude of Incoming 'Spikes'
  Add a filter close to the regulator input
  - inductor gives best performance for high load currents
  - resistor only suitable for low load currents - VDROP

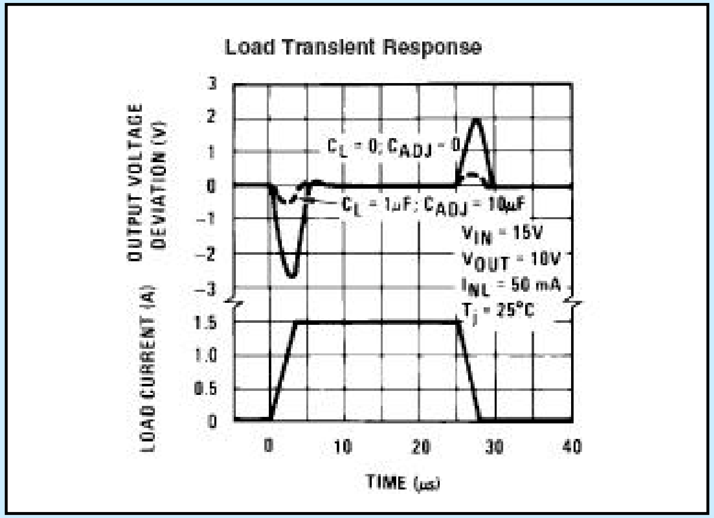


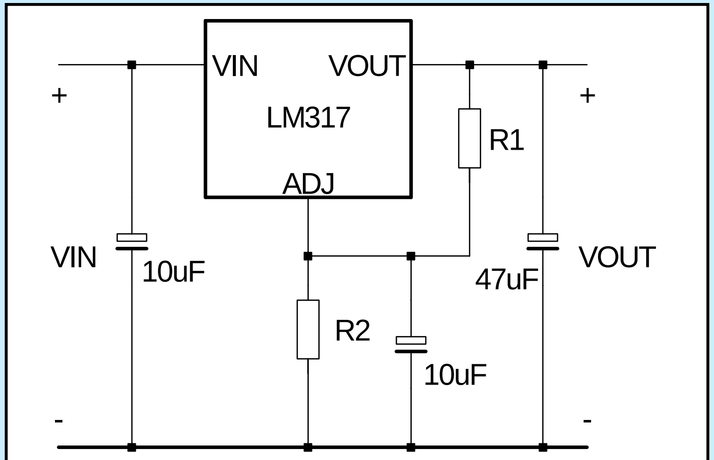



Reducing Input dV/dT

# Load Transient Response

- Load Transients
  - Change of VOUT if ILOAD changes suddenly
  - Regulator unable to cancel Fast Edges
  - Load Transients can be caused by operation of Infra-Red Sensors
  - Feeds directly onto CPU Supply
    - mild cases could cause random ADC Conversion errors
    - a bad case could lead to CPU brown-outs
- Possible Solutions
  - Choose a Regulator with a better Spec.
    - the LM317 shown is not good in this respect
    - the LM1117 is somewhat better
  - Fit a Tantalum Capacitor directly to Output
    - larger capacitor values generally give better results
  - For the LM317/ LM1117 fit a capacitor to the Adjustment Pin - say 10uF

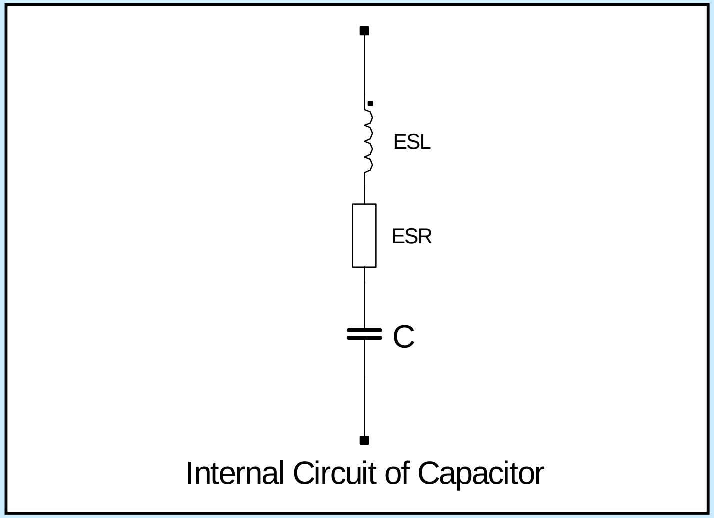


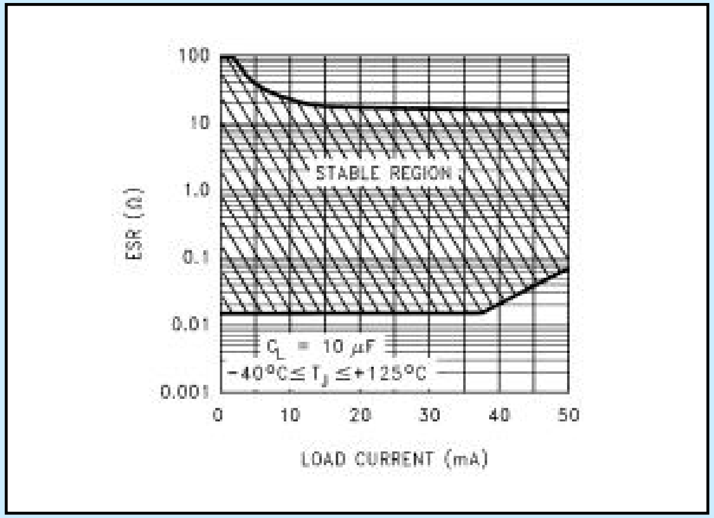
Improving Load Transient Response

# Output Capacitor ESR

- A bit of an Esoteric Subject but it is important for LDO Regulators
- Equivalent Series Resistance
  Capacitors have a small Internal Resistance
  They also have a small Internal Inductance
- Lower Diagram shows the Range of tolerable ESR vs Load Current for LP2980 LDO: $C_{OUT}$ = 10uF
- Capacitor Choice
  - Generally any Tantalum is OK
  - Low Value Al. Elecs. ESR may be too high
  - Beware of Multi-Layer Hi-Capacity Ceramics - they can have very low ESR values



Internal Circuit of Capacitor



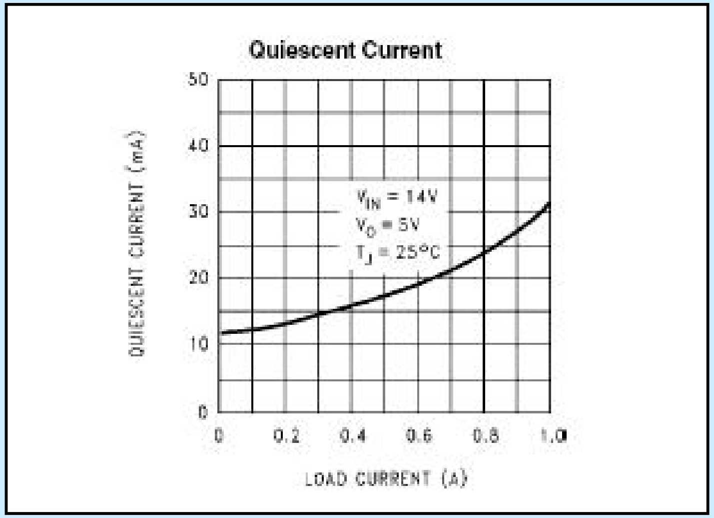
# Ground (or Quiescent) Current

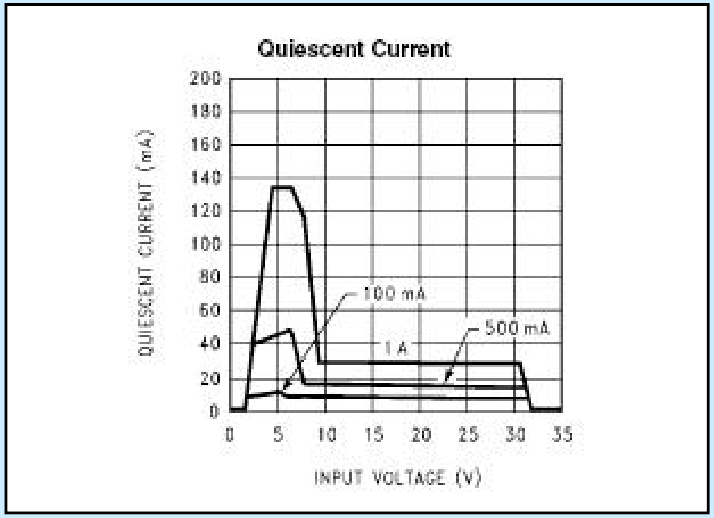
- Another Esoteric Subject but it is important for LDO Regulators

For the LM2940 regulator:

- Upper Graph
  Shows $I_{GROUND}$ vs $I_{OUTPUT}$ @ $V_{IO}$ = 9V
  - 12mA @ Iout = 0 rising to 30mA @ Iout = 1A
- Lower Graph
  Shows $I_{GROUND}$ vs $V_{IN}$ for various $I_{OUT}$
  Of special note is the 1A curve:
  - as Vin drops below 9V Iq rises rapidly
  - using an LM2940 to provide 5V @ 1A from 2-Cell LiPo pack would not be satisfactory - 500mA probably OK

NOTE: the graphs shown relate to the LM2940 5V/1A
- a first-generation LDO regulator
Second generation devices are better



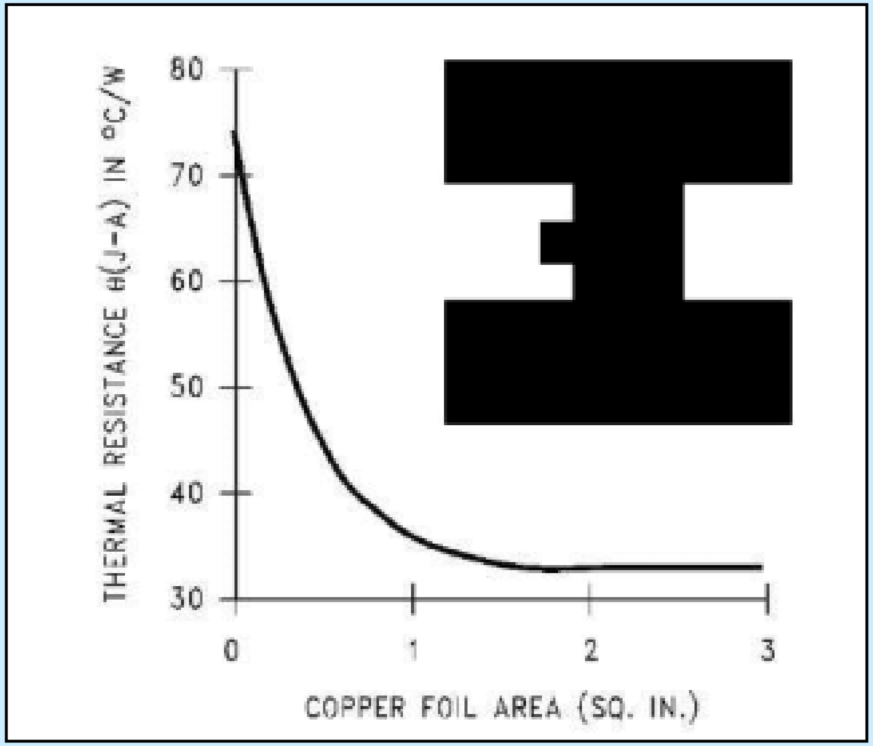



# Thermal Management - Sinking

- Linear Regulators Dissipate Heat - Sometimes Lots of It
  - using a 2-Cell LiPo pack to provide 5V @ 1A for Motors requires a regulator to dissipate 3W
  - this regulator needs a minimum heatsink of 30ºC/W to ensure reliability, and even with this:
    device junction temperature = (3 x 30) + 25ºC = 115ºC
    device case temperature approximately 100ºC !

It's not usually convenient to put a conventional heatsink on a Mouse:

- fabricate a 'heatsink' from copper zones on either, or both, sides
- can be used with:
  TO220 TH devices lying down
  TO252 SMD high-power devices
  SOT223 SMD medium power devices
- can be any shape - avoid narrow webs
- more than 1 VREG can spread the load



# Thermal Management - Sharing

- Method 1

  Neither Regulator needs to be an LDO

  - 5V device may need to be if VIN can fall below 7.5V

  PDISS 5V = 3V x 0.5A = 1.5W

  PDISS 3V = 5V x 0.1A = 0.5W

- Method 2

  3V (3.3V, 3.6V) Regulator must be an LDO

  - 5V device may need to be if VIN can fall below 7.5V

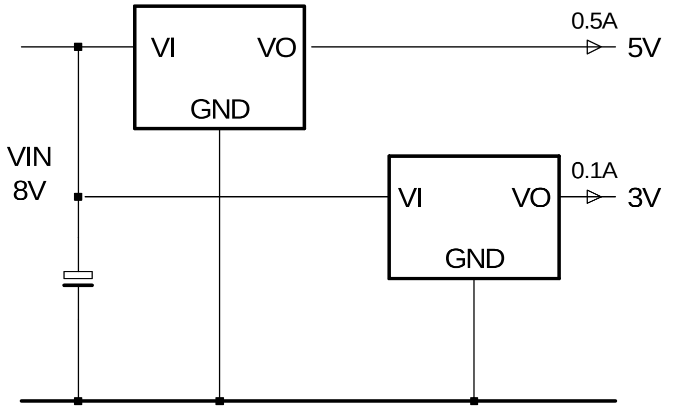
  PDISS 5V = 3V x 0.6A = 1.8W

  PDISS 3V = 2V x 0.1A = 0.2W

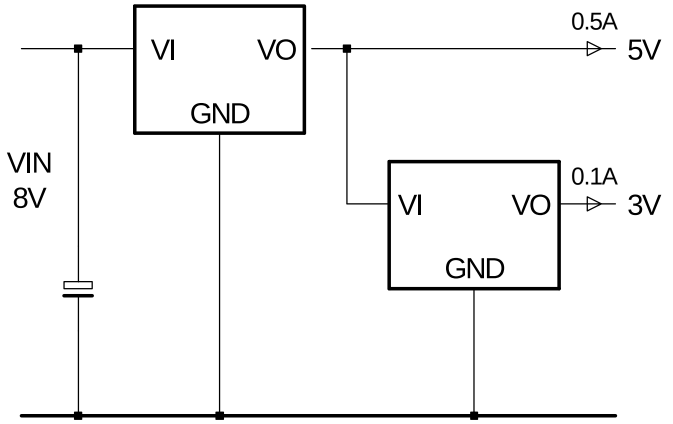
  Consider the following when deciding:-

  - carefully assess current drain on each supply
  - relative locations of the voltage source and the load
  - convenience of having a small local regulator for 3V
  - dissipating the resulting extra power in the 5V device
  - use the 'average' regulator dissipation - not the 'peak'

    (although using the peak value is conservative)



Dual Power Supply - Method 1

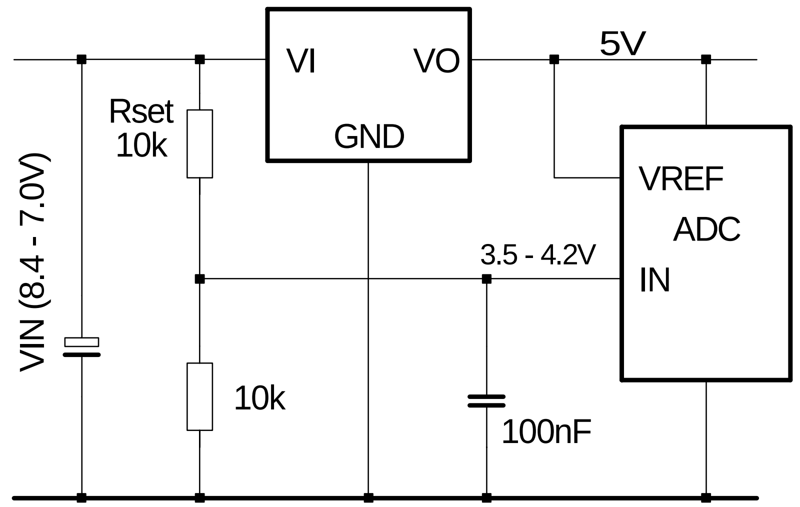


Dual Power Supply - Method 2

# Monitoring The Supplies

## Monitoring the Battery Voltage Provides an Early Warning

- as batteries discharge their Terminal Voltage reduces
- eventually it drops low enough to prevent the regulators operating correctly
- knowing this allows you to take some action - even if it just to shut the Mouse down




Monitoring the Battery Voltage

- Choose chain resistance to minimise power wastage - 0.5mA is OK
- 100nF at ADC input filters HF noise
- Choose RSET to utilise most of the ADC dynamic range
- Set 'Trip Point' just above VDROPOUT

- but, if using an LDO, consider battery end-of-life terminal voltage - it can fall very quickly - and set Trip Point accordingly

# PCB Layout

## This is where Science meets Art

### A Well Designed Layout Provides:-

- A Robust Platform for the Circuit
- Operational Reliability
- Measurement Accuracy from Low Noise
- Low-Noise

### We’ll Take a Look At:-

- The Golden Rule
- Various Possibilities for Tracking Power and Ground Traces
- The Use of Local Regulators
- A Few PCB Format Options

# Power and Ground Trace Rules

## The Golden Rule

*For Best Performance*

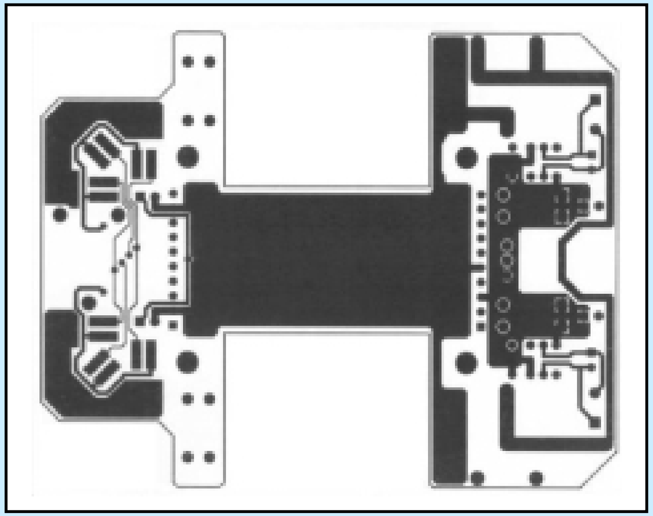
ALL Power and Ground Traces MUST be Wide!

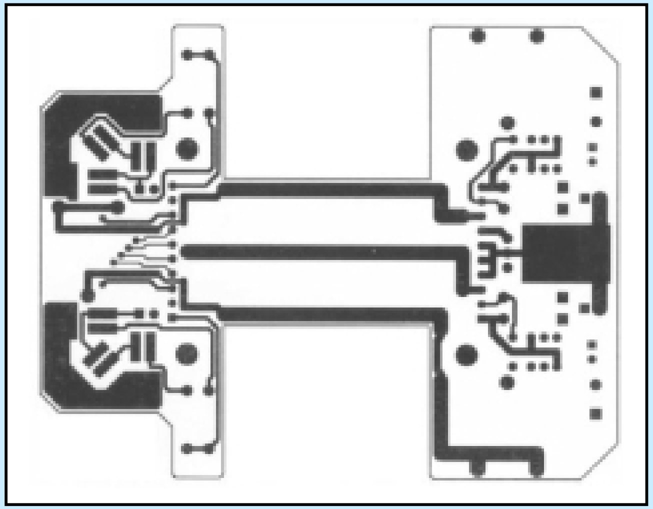
# Wide Power & Ground Tracks

## Left-Hand Wall Follower Power Board

- Bottom Side
  - Large Central Area is 0V (copper-fill technique)
  - Connects Front and Rear Areas Together
  - 'C' shaped area on RHS is +5V to Motors
  - Wide Track at RH End connects Batteries
- Top Side
  - Central Area at RHS is Regulator Heatsink
  - Central Wide Track is +5V to Sensors
  - Upper/Lower Wide Tracks connect Batteries

NOTE: The 'L' shaped copper areas at left are Light Shields for the Infra-Red Sensors





# Power and Ground Trace Rules

## Another Golden Rule

*For Best Performance*

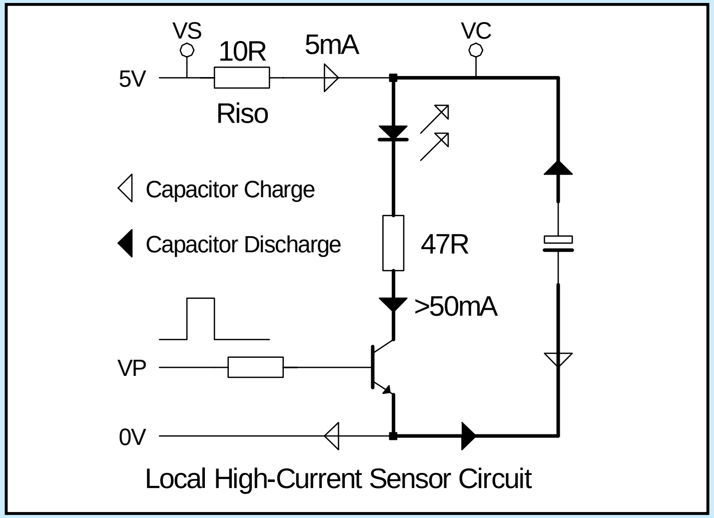
All Power and Ground Traces NEED NOT be Wide!

# Local High-Current Circuits

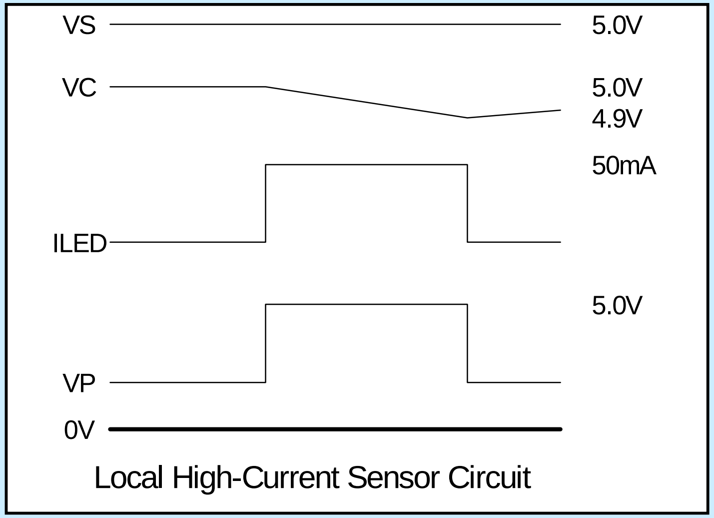
## Infra-Red Sensor Circuit

- High-Current Capacitor Discharge
  - LED Current determined by RDROP
  - Can be as high as 200mA - wide tracks
  - RISO limits current provided by main supply
  - Capacitor provides almost all energy
  - High Current path is very small and local
  - Return Current to Main Supply also limited
- Low-Current Capacitor Charge
  - Charging Current determined by VDROOP

    (5.0V - 4.9V) / 10R = 10mA max
  - Charge Current path may be extensive and laid with narrow tracks with no detrimental effect as current is low



Local High-Current Sensor Circuit

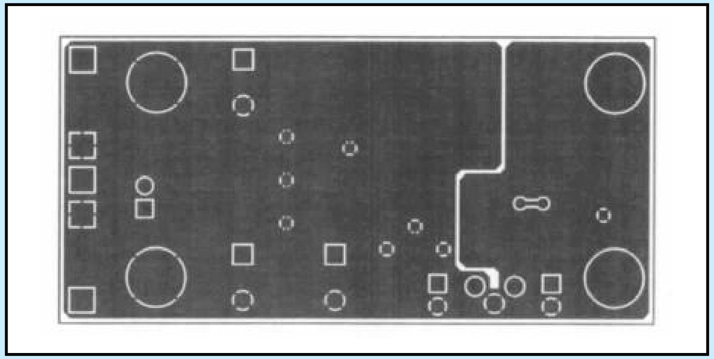


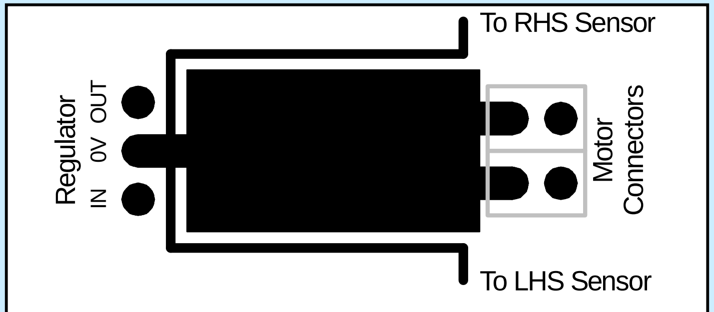
Local High-Current Sensor Circuit

# Tracking Power & Ground Traces

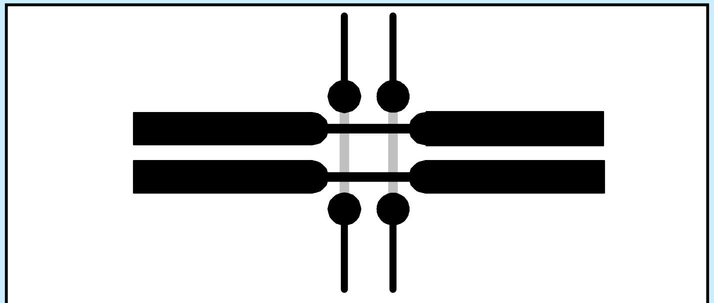
- Copper Flood (Fill) or Plane
  - Provides the lowest resistance
  - Provides the lowest inductance
  - Usually permits 'automatic' connectivity
  - Allows current paths to be determined if Zone Boundary is suitably described
- Star Points
  - Route each circuit's Return separately to 0V
  - Minimises Coupling of 0V-Line Interference
  - Permits separation of analogue and digital
- Track Necking
  - Each track is a series of small sections
    - wide tracks are low resistance sections
    - narrow tracks are high resistance sections
  - Maximise track width where possible
    - reduce it where necessary

Applies equally well to Power Traces as to Ground





Star Point - Return Separate Paths Direct to Regulator

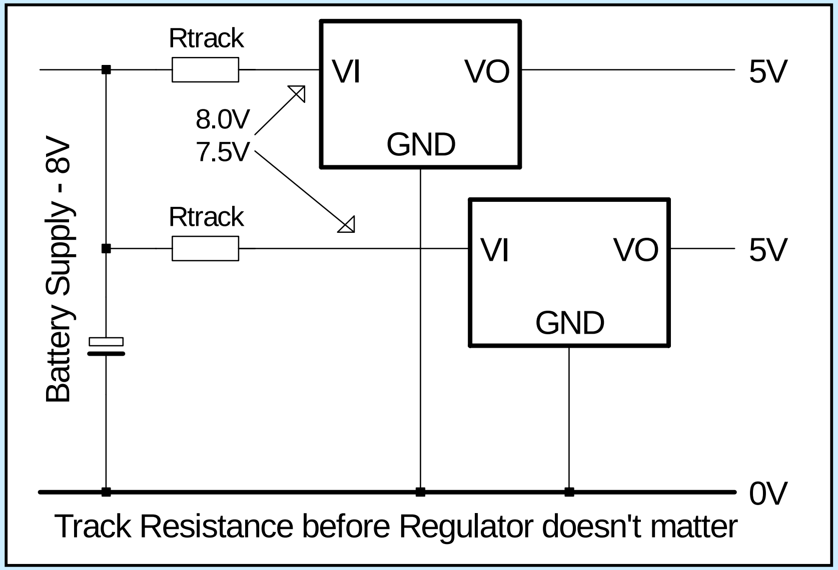

Track Necking to Squeeze Bewteen Pads

# Use Local Regulators

## Local Regulators Can Provide:

- Accurate Supply where it's Needed
- Lower Supply-borne Noise Levels
  (susceptibility and emissions - works both ways)
- Simplified PCB Tracking
  (low current supply feeds can be narrow)
- Special Odd-Value Supply Voltages
  (ADC References, Motor and/or Sensor Supplies)

For Low-Current Supplies the Regulator can be in a small package such as SOT23




Track Resistance on regulator supply side is not important - provided that the input voltage to the regulator does not fall below the level required to maintain regulation ($V_{OUT} + V_{DROP\text{-}OUT}$)

# Single or Multi-Layer Boards ?

## Single-Sided Board

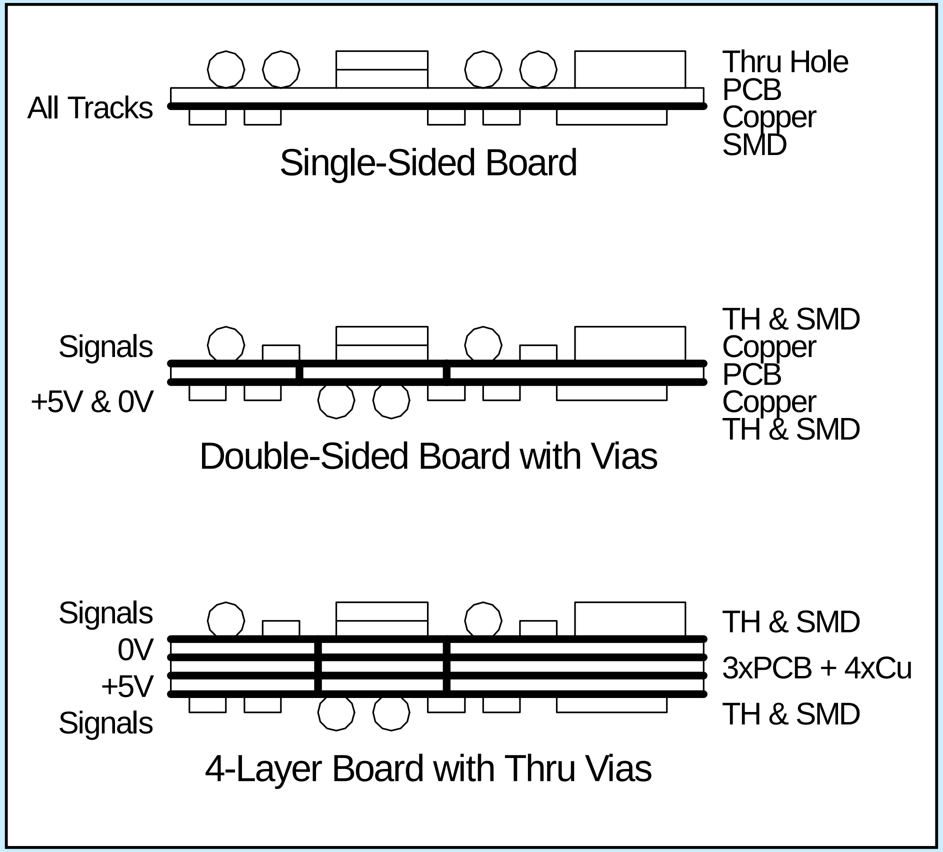
- Copper Layer on One Side Only - Cheapest
- Power, Ground and Signals all on One Layer
- Difficult to Route anything but Simple Layouts
  almost always needs 'jumper links' - takes space

## Double-Sided Plated Thru Hole

- Copper Layers on Both Sides
- Layers can be Joined using Plated Thru Vias
- Can Separate Power & Ground and Signals
- Routing is Easier due to 'Escape Routes'
- Reasonably Priced from Specialist Suppliers

## Multi-Layer Board

- 4 < or more > Copper Layers in a Sandwich
- Permits Extensive use of Copper Planes
- Can Dedicate Layers to Power & GND Planes
- Rather Expensive
  but that's OK if you happen to know an MP!



# Determining Track Widths

- PCB Copper Foil is specified as the 'Weight of Copper per Sq. Foot'
- Typical Weights are 0.5, 1 and 2 ounces - 1oz being most common
- Heavier Copper gives greater Thickness - Lower Resistance

(Note that, even in this metric age, values are still usually given in Imperial Units)

## Common PCB Statistics

- Copper Weight 1oz
- Copper Thickness 1.37mils

The table gives 'specific resistance' and typical current carrying capacity for various 1oz weight track widths

Scale as appropriate for 0.5oz and 2oz

| PCB Track Characteristics for 1oz Copper | | | |
|---|---|---|---|
| | | | |
| Width (in) | Width (mm) | Ohms/Inch | Max Current |
| 0.005 | 0.125 | 0.100 | 0.5A |
| 0.010 | 0.250 | 0.050 | 0.9A |
| 0.015 | 0.375 | 0.033 | 1.2A |
| 0.020 | 0.500 | 0.025 | 1.5A |
| 0.025 | 0.625 | 0.020 | 1.7A |
| 0.050 | 1.250 | 0.010 | 2.8A |
| 0.100 | 2.500 | 0.005 | 4.5A |

Typical 1oz-Copper PCB Statistics

# In Summary

- Know your Circuit's Supply Voltage Requirements
- Know the Range of Battery Voltage:
  - use maximum to calculate regulator power dissipation
  - use minimum to determine regulator type - Standard or LDO
- Carefully read the Regulator's Datasheet
  - try to understand what it is telling you
  - try to fathom out what it is NOT telling you
- Determine Regulator arrangement in Multi-Supply Systems
  - is it better to power both direct from the battery - or one from the other
- Estimate the Power Dissipation in each Regulator
- Estimate the size of any necessary Heatsinking arrangement
  - a 0.5 sq.in copper-zone sink can safely dissipate about 1W - maybe 1.5W
  - a wide 0V track can do double-duty - acting as a heatsink too
- Plan 0V & Power Routing early in the layout process
  - signal tracks having to 'hop over' power tracks is better than the other way round
- Don't be afraid to change the Schematic - even during Layout
  - sometimes adding an extra sub-circuit or component can ease a layout problem

# Power & Ground Systems

*That's all Folks*