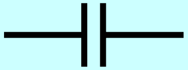
Common Electrical Components in Oceanographic Systems

Reviewing Basics

- *Kirchoff's Voltage rule*: voltages V at a node are the same.
- *Kirchoff's Current rule*: sum of currents i flowing into and out of a node is zero.
- Analogy: Voltage is like fluid pressure, current is like fluid volumetric flow rate. The wire is like a pipe.

- Resistor R: V = IR,
  - Dissipation: Resistive Power $P = I^2R = V^2/R$
  - Analogy: viscous losses in pipe flow

- Capacitor C: i = C dV/dt
  - Analogy: a hydraulic accumulator

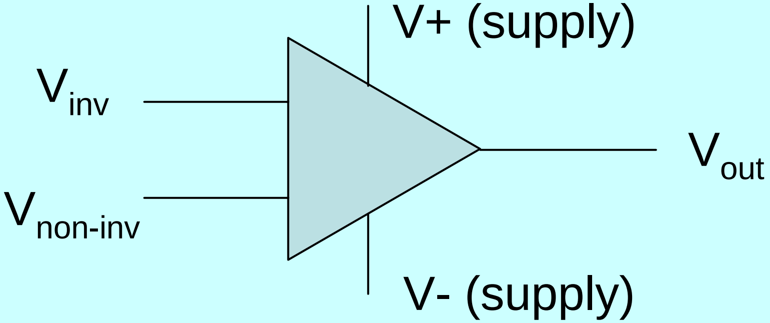


- Inductor H: V = L di/dt
  - Analogy: inertia of water in a pipe

The Op-Amp

Two inputs (called inverting and non-inverting); one output.

The output voltage is a HUGE gain multiplied by the difference between the inputs.



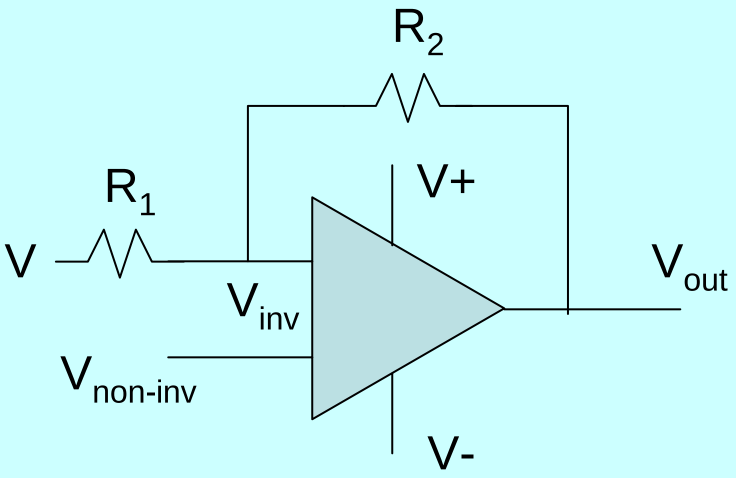
Horiwitz’s & Hill’s golden rules:

a. The op-amp enforces (in proper use)

$$V_{inv} = V_{non\text{-}inv}$$

b. No current flows into the device at either input

Example Op-Amp: Adding a Voltage Bias



$(V-V_{inv})/R_1 = (V_{inv}-V_{out})/R_2$ and

$V_{inv} = V_{non\text{-}inv}$ →

$VR_2 = V_{inv}(R_1+R_2) - V_{out}R_1$ →

$V_{out} = V_{non\text{-}inv}\,(R_1 + R_2)/R_1 - VR_2/R_1$

Letting R1 = R2, then

$V_{out} = 2V_{non\text{-}inv} - V$

The circuit inverts the input V and adds on 2$V_{non\text{-}inv}$

IF V_{non_inv} is ground, then V_{out} is –V. This is just an inverting amplifier.

Voltage bias useful for bringing signal levels into the range of sensors.

The op-amp is discussed in detail by Horowitz and Hill, covering integrators, filters, etc.

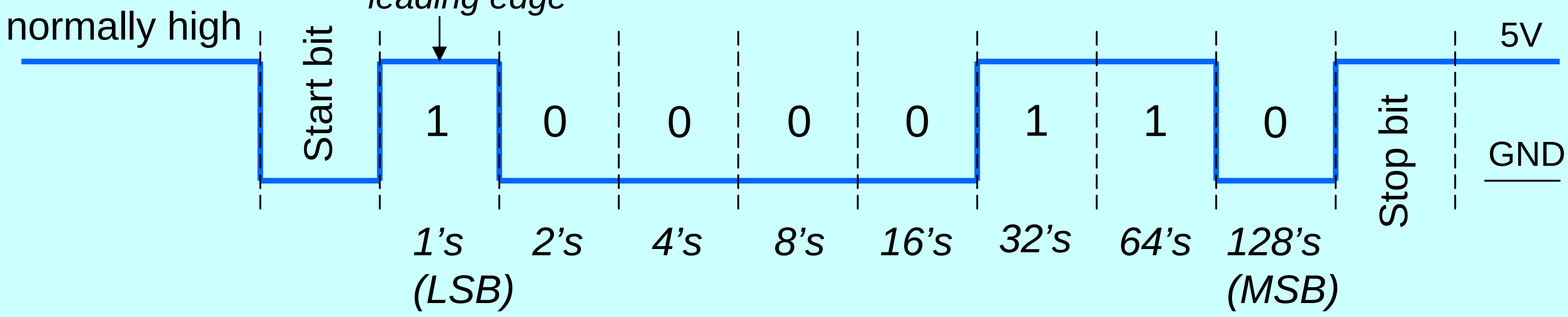
Serial Communications

- *How to transmit digital information fast and reliably over a few wires?*
- Examples: RS-232, RS-485, etc. refer to pins & wires
- A minimal case of RS-232 (DB25 connector is full case):
  - Asynchronous operation; both sides agree on BAUD rate
  - Three wires: send (TX), receive (RX), ground
  - No error checking! No flow control!

EXAMPLE using CMOS components:

Successive bits read at midpoints, based on baud rate and on start bit leading edge

64 + 32 + 1 = 97 = ‘a’



EXAMPLE: A GPS String

- Garmin GPS25 series – Smart embedded device!
- Similar to TT8's interface with you – I/O strings are passed through a serial port
- Reconfigurable through special commands
- Output at 1Hz
- String maintains <u>exactly</u> the same syntax: e.g.,

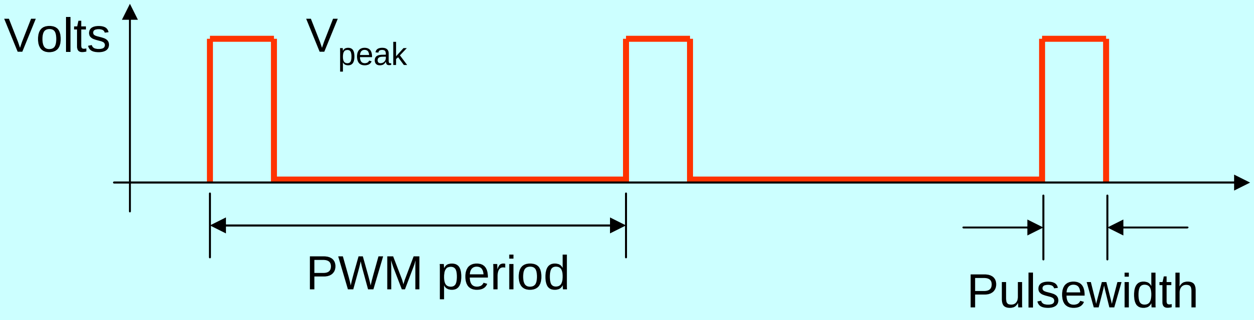
$GPRMC,hhmmss,V,
ddmm.mmmm,N,dddmm.mmmm,E,
000.0,000.0,ddmmyy,000.0,E,N,*XX<CR><LF>

➔ *73 chars appear as one line:*

$GPRMC,hhmmss,V,ddmm.mmmm,N,dddmm.mmmm,E,000.0,000.0,ddmmyy,000.0,E,N,*XX

Pulse Width Modulation

- A Regular Waveform



- PWM frequency (Hz) = 1 / PWM period
- Duty cycle = Pulsewidth / PWM period
- PWM frequencies typically range from 100Hz into MHz
- Duty cycles can be used from 0 – 100%, although some systems use much smaller ranges, e.g. 5-10% for hobby remote servos.
- The waveform has two pieces of information: Period and Pulsewidth, although they are usually not changed simultaneously.

Some PWM Uses

- The Allure: very fast, cheap switches and clocks to approximate continuous processes. Also, two-state signal resists noise corruption.
- <u>Sensors</u>: PWM period is naturally related to *rotation or update rate*: Hall effect, anemometers, incremental encoders, tachometers, etc.
- <u>Communication</u>: PWM duty cycle is *continuously variable* → like an D/A and an A/D.
- <u>Actuation</u>: At very high frequencies, physical systems filter out all but the mean; i.e.,

$$V_{effective} = duty\_cycle * V_{peak}$$

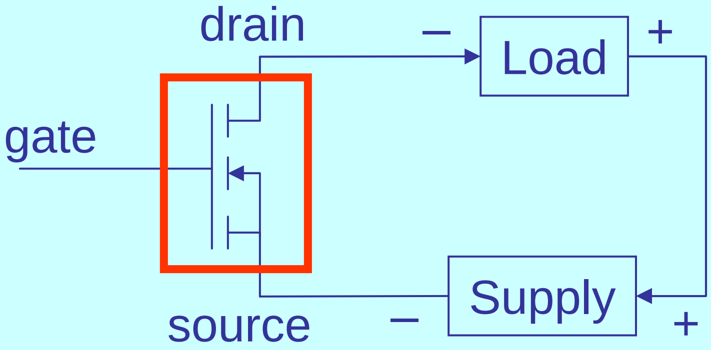
High frequency switching is the dominant mode for powering large motors!

Image removed for copyright reasons.

Field Effect Transistor (FET)

- Like a "valve", that is very easy to open or close. When FET is open, resistance is low (milli-Ohms); when FET is closed, resistance is high (mega-Ohms or higher)

- Typically three connections:
  - Gate: the signal; low current
  - Source: power in
  - Drain: power out



- *N*- and *P*-type junctions are common, and involve the polarity of the device. (*N* is shown)
- Extremely sensitive to static discharge! *Handle with care.*
- MOSFET: modern FET's capable of handling higher power levels → PWM power.

The Basic DC Brush Motor

Torque τ ←→ (coils)(flux density)(current i), or, in a given motor,

$\tau = k_t * i$ where k_t is the torque constant

But the motion of the coils also induces a voltage in the coil, the back-EMF:

$e_b = k_t * \omega$ *(YES, that's the same* k_t*!)*

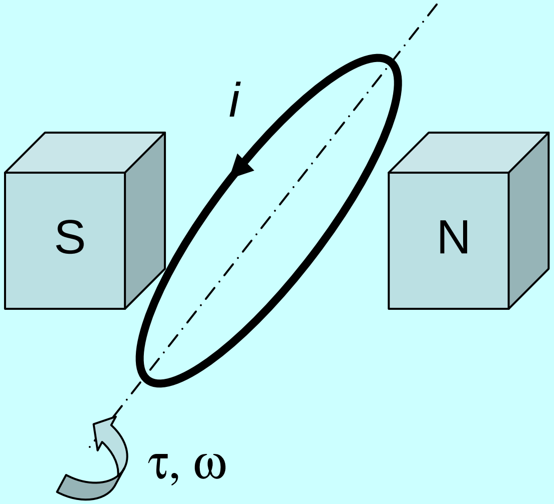
And the windings have a resistance R:

$e_R = R * i$

Summing voltages around the loop,

$V_{supply} = e_b + e_R$

Vector relations:
force = current x flux
field = velocity x flux



Properties of the DC Brush Motor

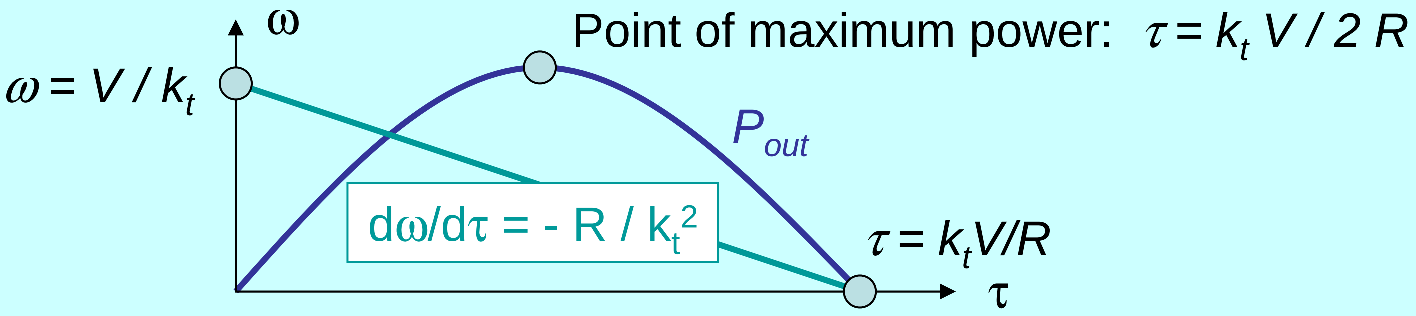
- No-load speed:

  $\tau = 0 \rightarrow i = 0 \rightarrow$ $\boldsymbol{\omega = V / k_t}$
- Zero-speed torque (*BURNS UP MOTOR IF SUSTAINED*):

  $\omega = 0 \rightarrow e_b = 0 \rightarrow i = V / R \rightarrow$ $\boldsymbol{\tau = k_t V / R}$
- Power output:

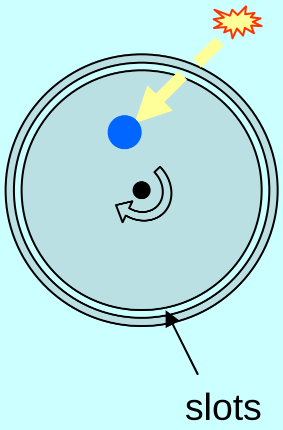
  $P_{out} = \tau\,\omega = i\,e_b \rightarrow$ $\boldsymbol{P_{out} = i\,(V - Ri)}$
- Efficiency:

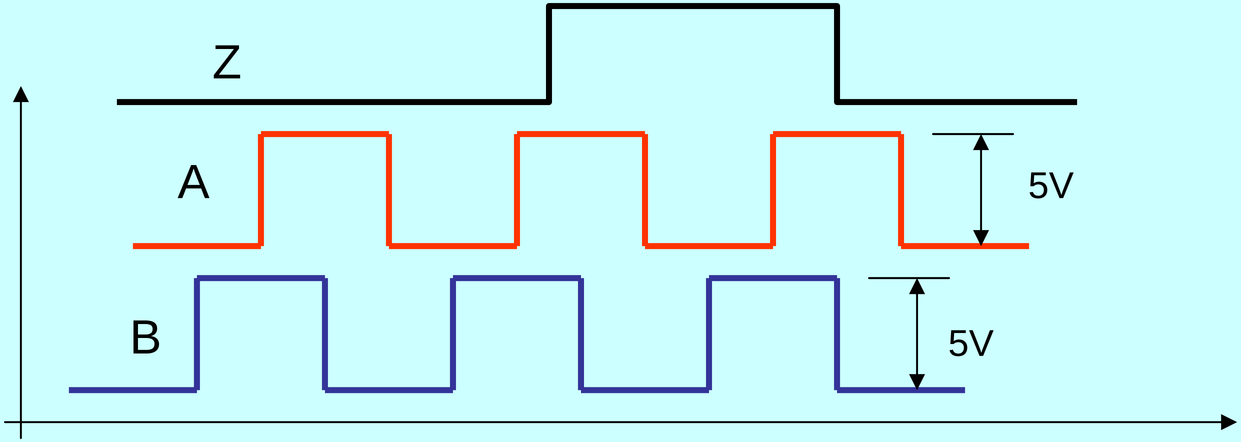
  $\eta = P_{out} / P_{in} = \tau\,\omega / i\,V \rightarrow$ $\boldsymbol{\eta = 1 - i\,R / V}$



Incremental Encoders

- *What is the position of the shaft?*
- Take advantage of cheap, fast counters → make a large number of pulses per revolution, and count them!
- Advantages of the incremental encoder:
  - High resilience to noise because it is a digital signal
  - Counting chip can keep track of multiple motor turns
  - Easy to make – phototransistor, light source, slotted disk
- Two pulse trains required to discern direction: *quadrature*



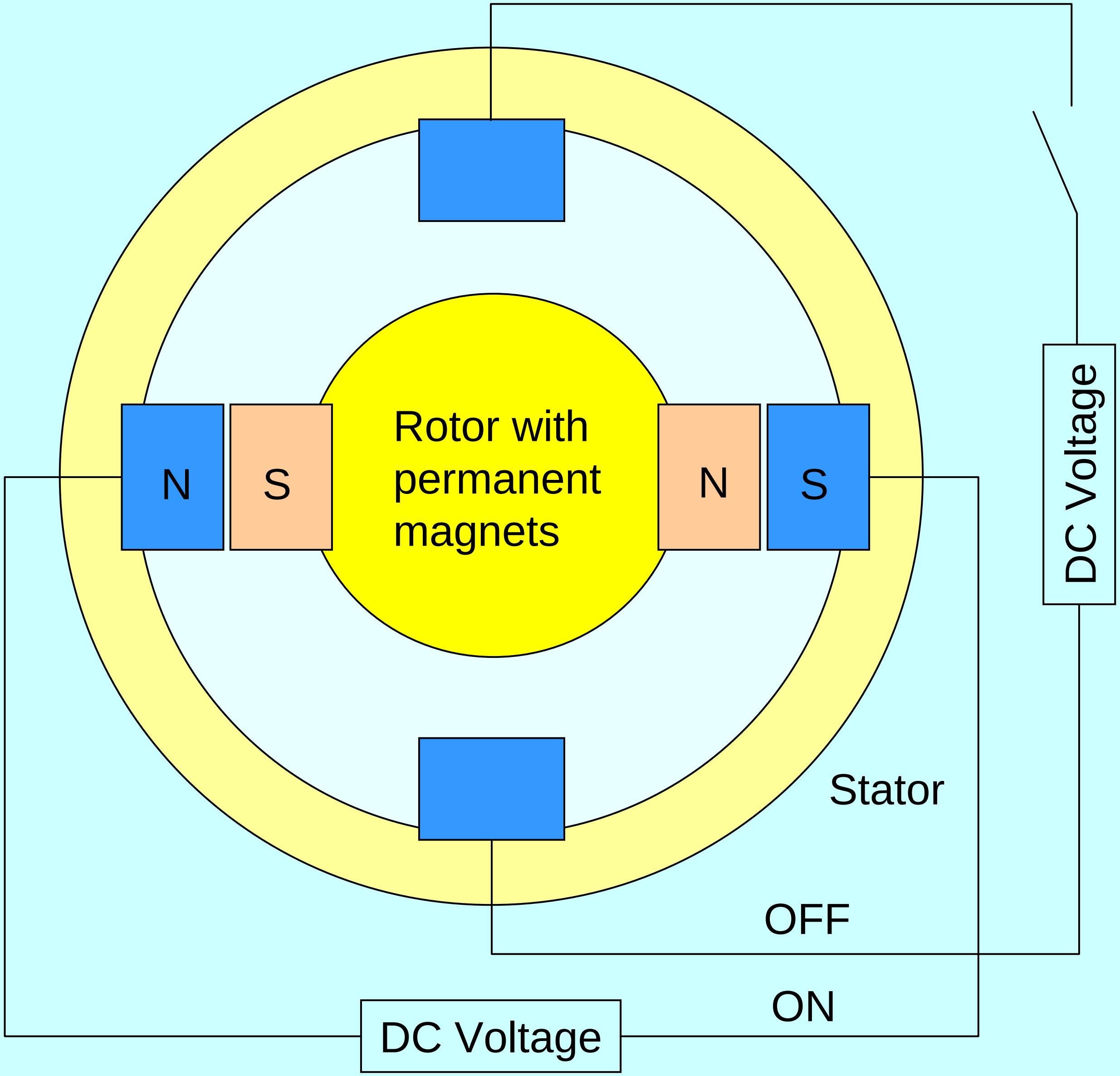


Stepper Motors

Switched coils at fixed positions on the stator attract permanent magnets at fixed positions on the rotor.

Smooth variation of switching leads to half-stepping and micro-stepping

Encoder still recommended!



Embedded Microprocessors

- *What defines microprocessors* → They are primarily made of switches: thousands or millions of small, cheap, and extremely fast switches.
- *Embedded = used for a specific task or subsystem.* A car has hundreds of embedded microprocessors, e.g., smart sensors, switches, displays, etc.
  - No user programming in an embedded microprocessor.
  - Real-time operation.
- Why embedded microprocessors instead of circuits?
  - Versatile, cheap, common, reliable, reprogrammable, etc.

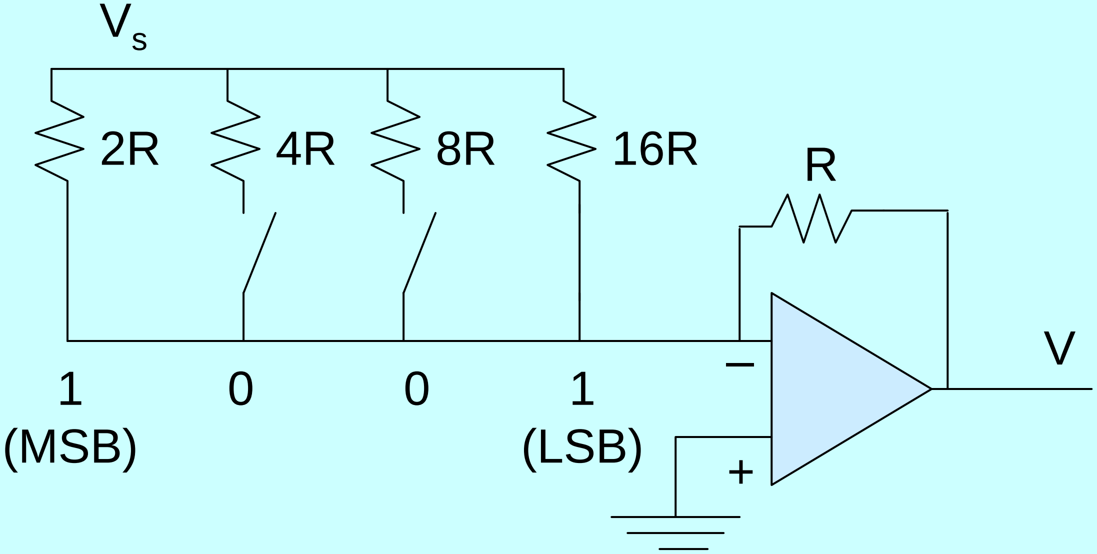
Major Issues with Embedded Microprocessor (EMB) Applications

- **Fast** EMB signals vs. **slow** signals from peripherals
- **Low-power** EMB signals vs. **high-power** peripherals
- Interfacing EMB **data space** with peripheral devices' data
- **Digital** (switched: ON or OFF) vs **analog** information (continuously variable)
- **Parallel** digital (one bit per wire) vs. **serial** digital communication (bits sent sequentially over one wire).
- <u>All relevant to the TT8!</u>

Digital to Analog Conversion (D/A)

If setting is [1,0,0,1], then
R_e = 1 / (1/2R + 1/16R) = 16R/9 and
V = -R/R_e*V_s = -9/16 * V_s = -0.5625 V_s

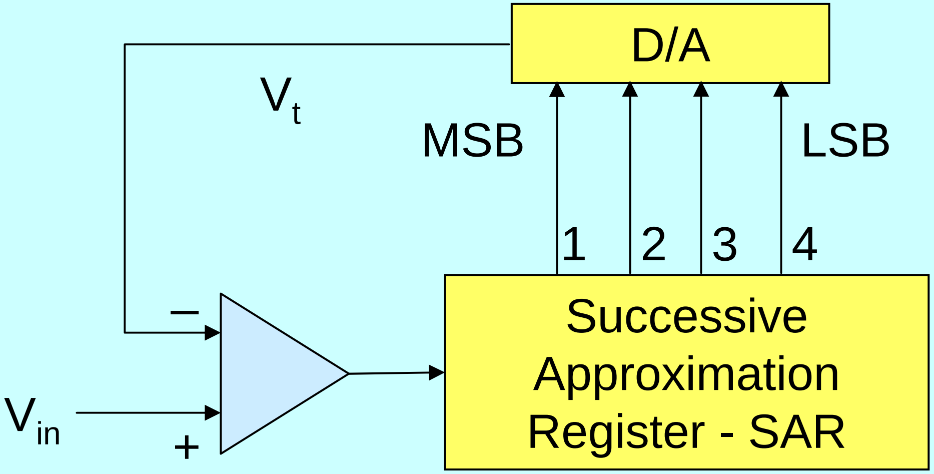
If R_e = OPEN,	i.e., [0,0,0,0],	then V = 0	MIN VALUE
If R_e = 16R,	i.e., [0,0,0,1],	then V = -0.0625*V_s	
If R_e = 2R,	i.e., [1,0,0,0],	then V = -0.5000*V_s	
If R_e = 16R/15,	i.e., [1,1,1,1],	then V = -0.9375*V_s	MAX VALUE



Resolution:
$V_s/2^N$ where N is the number of switches, or V_s/16 in this case.

Analog to Digital Conversion (A/D)

- Uses a comparator (op-amp) and a D/A converter.



The idea:

- Set bit k
- Do the D /A conversion
- If $V_t > V_{in}$, leave bit set
  Else reset bit
- Go through all the bits

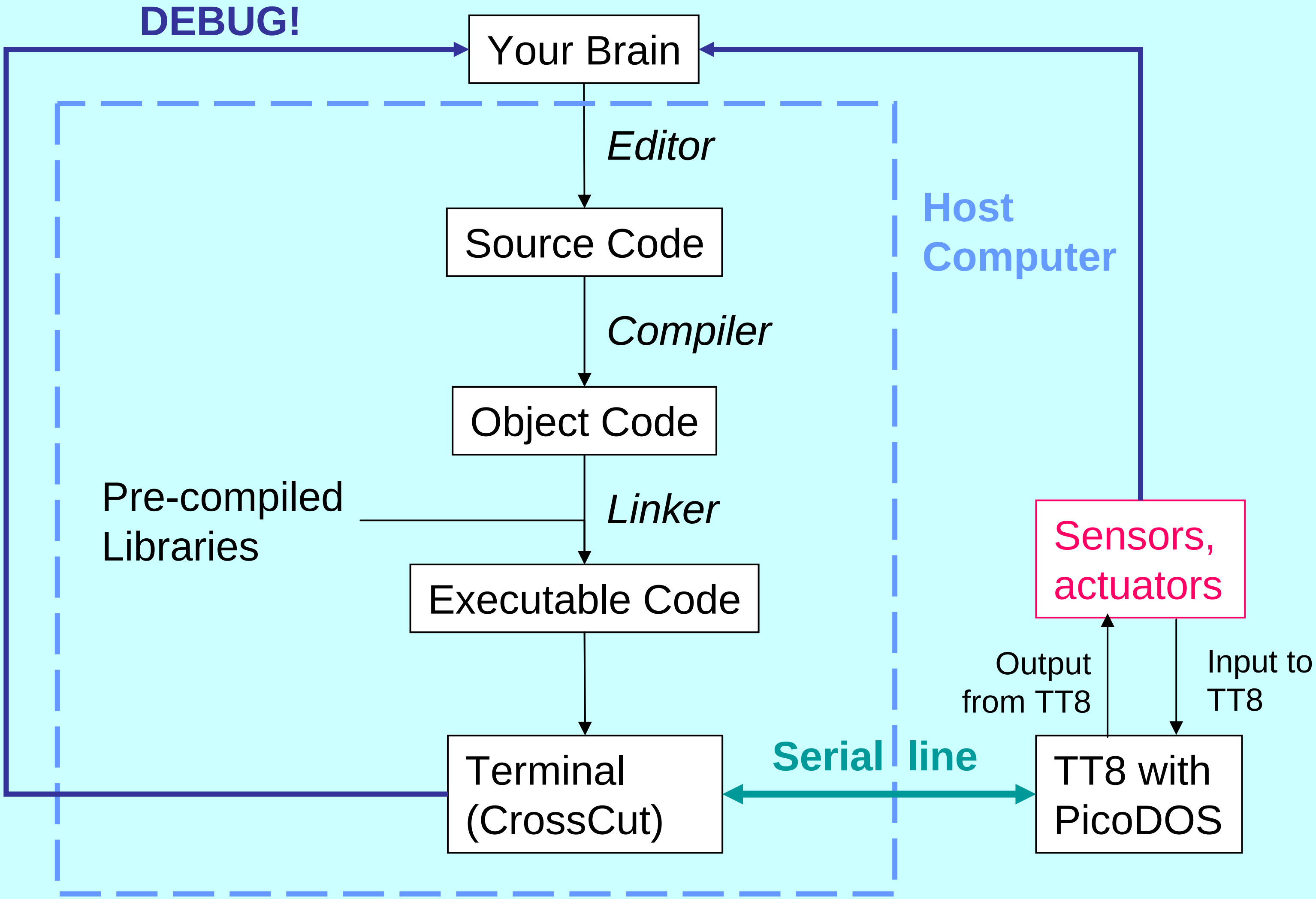
The SAR and D/A are typically used multiplexed because they are so fast!

Step	SAR	Compare	Decision
1	1000	$V_t < V_{in}$	Leave bit set
2	1100	$V_t > V_{in}$	Reset bit
3	1010	$V_t > V_{in}$	Reset bit
4	1001	$V_t < V_{in}$	Leave bit set

DONE!

What is the Onset TattleTale Model 8?

- A *small, low-power, inexpensive, and self-contained* system for mobile data acquisition, control, and computing.
- Can be compared to PC-104, Octagon, etc.
- Why do we use the TT8? The board off-the-shelf can do an extremely wide array of tasks:
  - Motorolla 68332 processor
  - analog A/D (8 channels,12 bit)
  - Digital i/o lines (at least 14; these can all be configured as serial lines or PWM inputs/outputs)
  - Two dedicated serial ports for you to program with
  - Expandable memory to 64MB (and more by now) → an exceptional platform for data logging


DEBUG!

Your Brain

Editor

Source Code

Compiler

Object Code

Pre-compiled
Libraries

Linker

Executable Code

Terminal
(CrossCut)

Serial line

TT8 with
PicoDOS

**Host
Computer**

Sensors,
actuators

Output
from TT8

Input to
TT8

Power Sources for Marine Systems

Characteristics of Power Systems for Marine Applications

- “Main Supply” of power – energy source must be carried on board; has to last days, months, years.
- Weight and volume constraints *may* be significantly reduced compared to terrestrial and esp. aeronautical applications.
- Reliability and safety critical due to ocean environment.
- Capital cost, operating costs, life cycle analysis, emissions are significant in design, due to large scale.

This Lecture

- Fuel Engines
  - Characteristics of typical fuels; combustion
  - Internal combustion engines
  - Brayton cycle (gas turbine) engines

- Batteries and Fuel Cells
  - Electrochemical processes at work
  - Canonical battery technologies
  - Fuel cell characteristics

- NOT ADDRESSED: Nuclear power sources, renewable energy, emissions, green manufacturing, primary batteries, generators … !

Engines transform *chemical* energy into *heat* energy into *mechanica*l or *kinetic* energy.

1 MegaJoule is:

1 kN force applied over 1 km;

1 Kelvin heating for 1000 kg air;

1 Kelvin heating for 240 kg water;

10 Amperes flowing for 1000 seconds at 100 Volts

Fuel	**Heat Content MJ/kg**
Gasoline*: C_8H_{15}	45
Diesel*: $C_{13}H_{23}$	42
Propane: C_3H_8	48
Hydrogen: H_2	130
Ethanol: C_2H_50H	28

**Approx.: complex mixtures*
Pulkrabek, p. 444

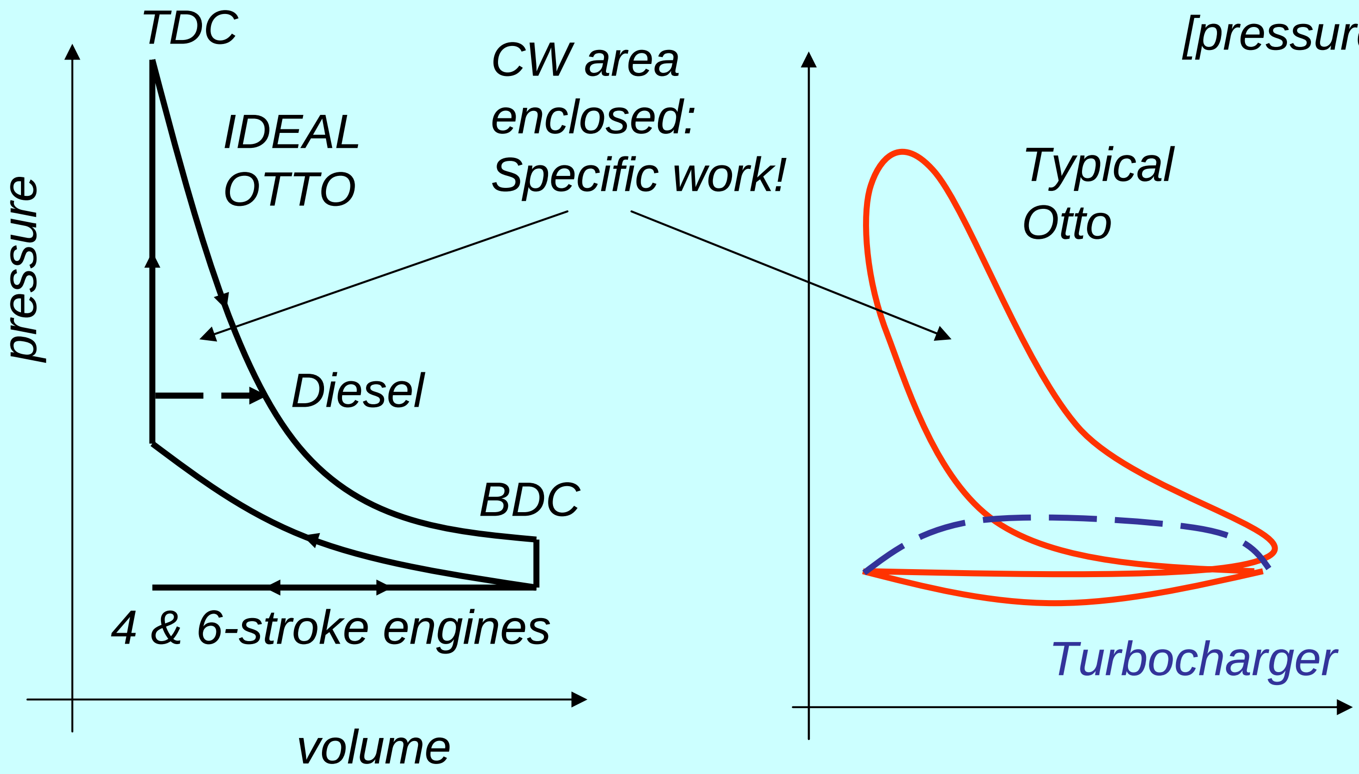
Reaction for gasoline:

$$\mathbf{4\ C_8H_{15} + 47\ O_2 \rightarrow 30\ H_2O + 32\ CO_2} \textbf{ + other products}$$

Otto and Diesel Cycles

Four-stroke engine:

1: TDC to BDC, bring air into cylinder
2: BDC to TDC, compress air
ADD FUEL and IGNITE!
3: TDC to BDC, expand heated air (power stroke)
4: BDC to TDC, blow out products of combustion



*[pressure * volume] =*
$N/m^2 * m^3/kg$ =
Nm/kg =
Energy/mass

Typical ICE efficiency to BHP: 30%

Typical power density: 0.05-0.4 kW/kg

Pulkrabek p. 88, 111.

Image removed for copyright reasons.

Please see: http://www.power-technology.com/projects/combined-cyclegasturbine(ccgt)_gallery.html

9H combined-cycle gas turbine

GE LM2500 gas turbine:
22kW for marine propulsion

Image removed for copyright reasons.

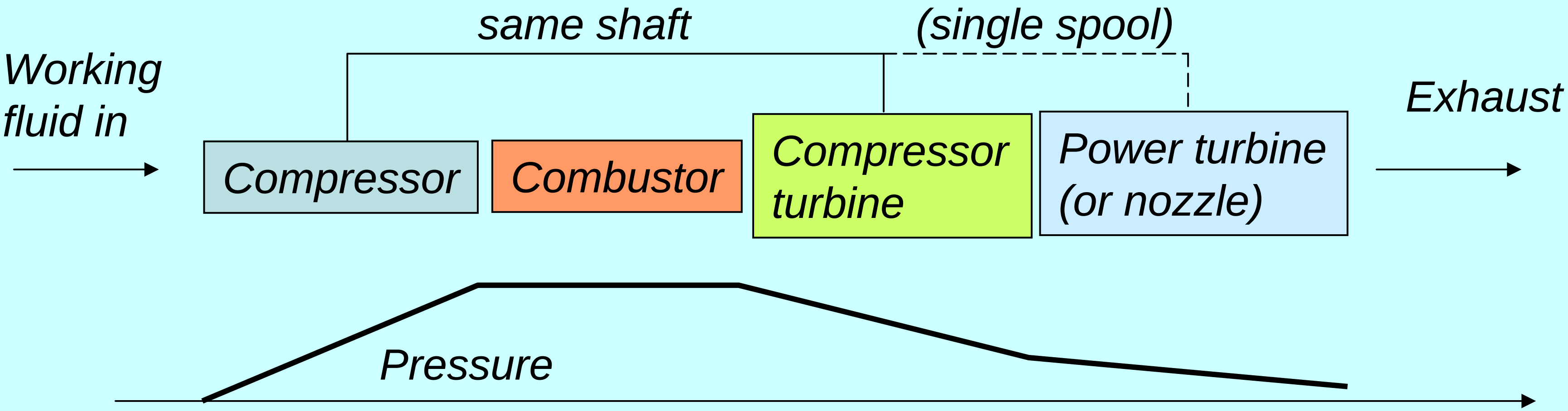
Please see: http://www.aircraftenginedesign.com/enginepics.html

LM2500 Specifications - Quoted

“ Output: 33,600 shaft horsepower (shp)
Specific Fuel Consumption: 0.373 lbs/shp-hr
Thermal Efficiency: 37%
Heat Rate: 6,860 Btu/shp-hr
Exhaust Gas Flow: 155 lbs/sec
Exhaust Gas Temperature: 1,051°F
Weight: 10,300 lbs
Length: 6,52 meters (m)
Height: 2.04 m

Average performance, 60 hertz, 59°F, sea level, 60% relative humidity, no inlet/exhaust losses, liquid fuel, LHV=18,400 Btu/lb ”

http://www.geae.com/aboutgeae/presscenter/marine/marine_200351.html



same shaft

(single spool)

Working fluid in

Compressor

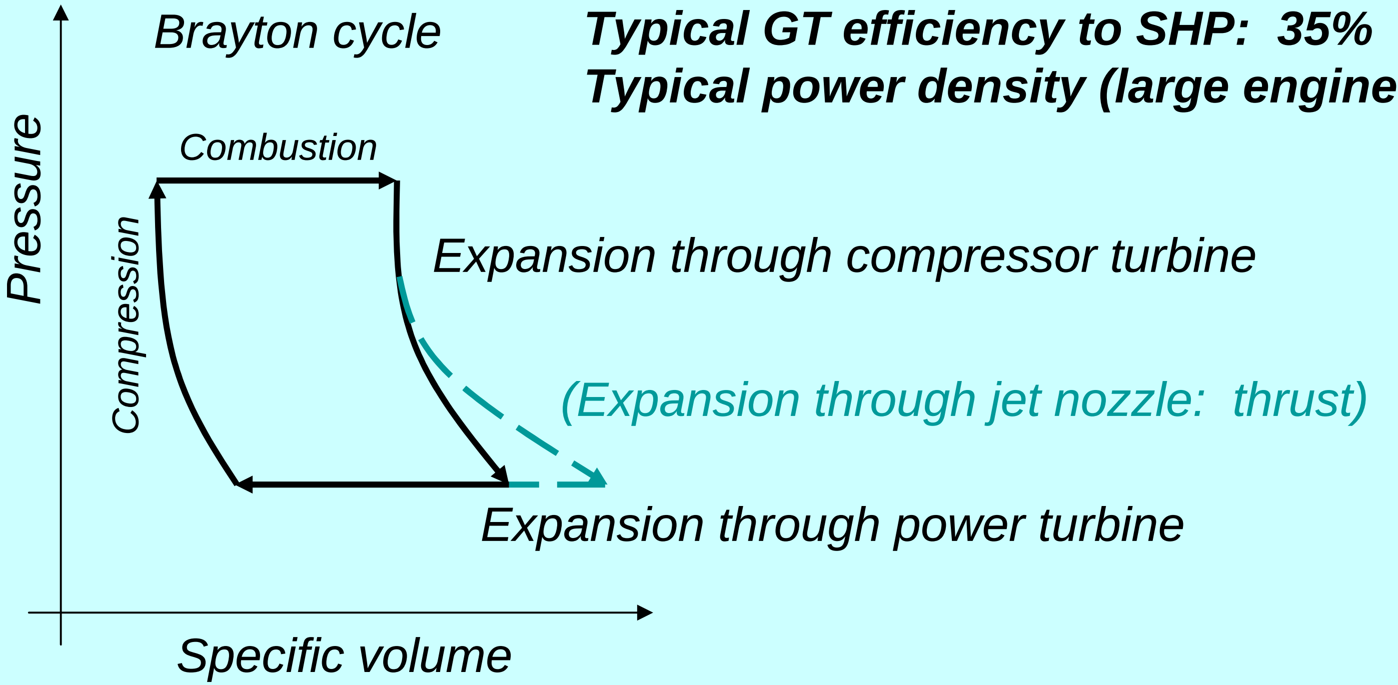
Combustor

Compressor turbine

Power turbine (or nozzle)

Exhaust

Pressure



Brayton cycle

Pressure

Combustion

Compression

Expansion through compressor turbine

(Expansion through jet nozzle: thrust)

Expansion through power turbine

Specific volume

Typical GT efficiency to SHP: 35%

Typical power density (large engines): 5 kW/kg

Giampaolo, p. 46, 52

Battery Technologies

Electrochemical Cells

Lead-acid battery has two electrode reactions (discharge):

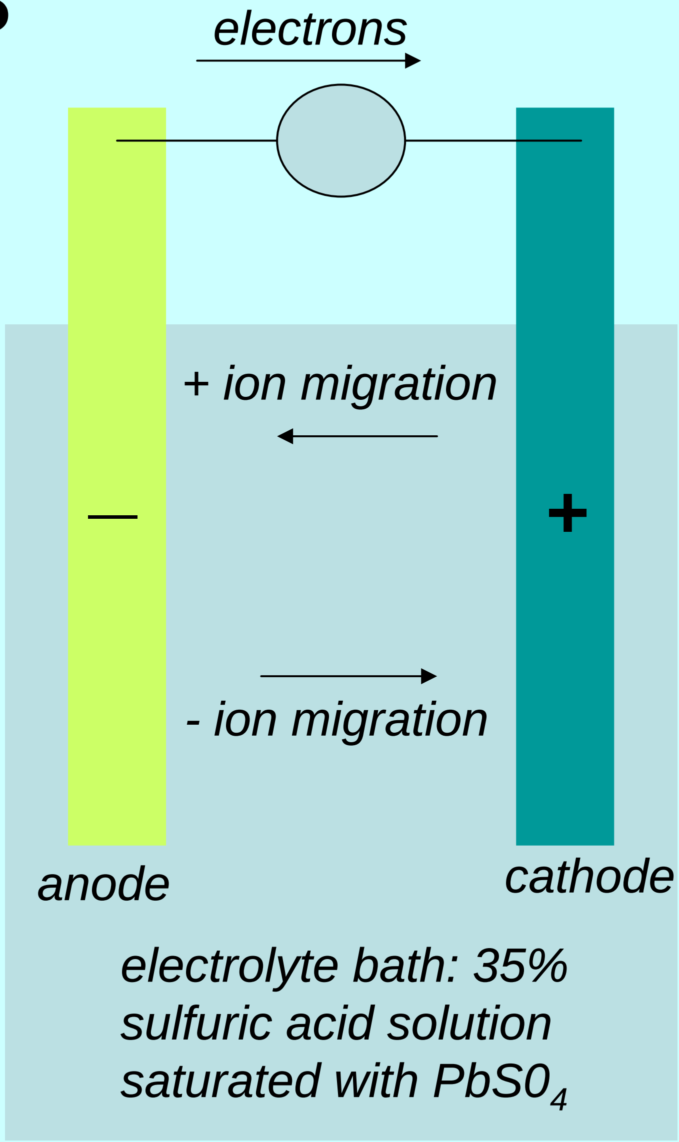
Releasing electrons at the negative electrode:

$Pb \rightarrow Pb^{2+} + 2e^-$ (oxidized)
or
$Pb + S0_4^{2-} \rightarrow PbSO_4 + 2e^-$

Gathering electrons at the positive electrode:

$Pb^{4+} + 2e^- \rightarrow Pb^{2+}$ (reduced)
or
$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Total Chemistry of the Lead-Acid battery:
$Pb + PbO_2 + 2\ S0_4^{2-} + 4H^+ \rightarrow 2\ PbSO_4 + 2\ H_2O$

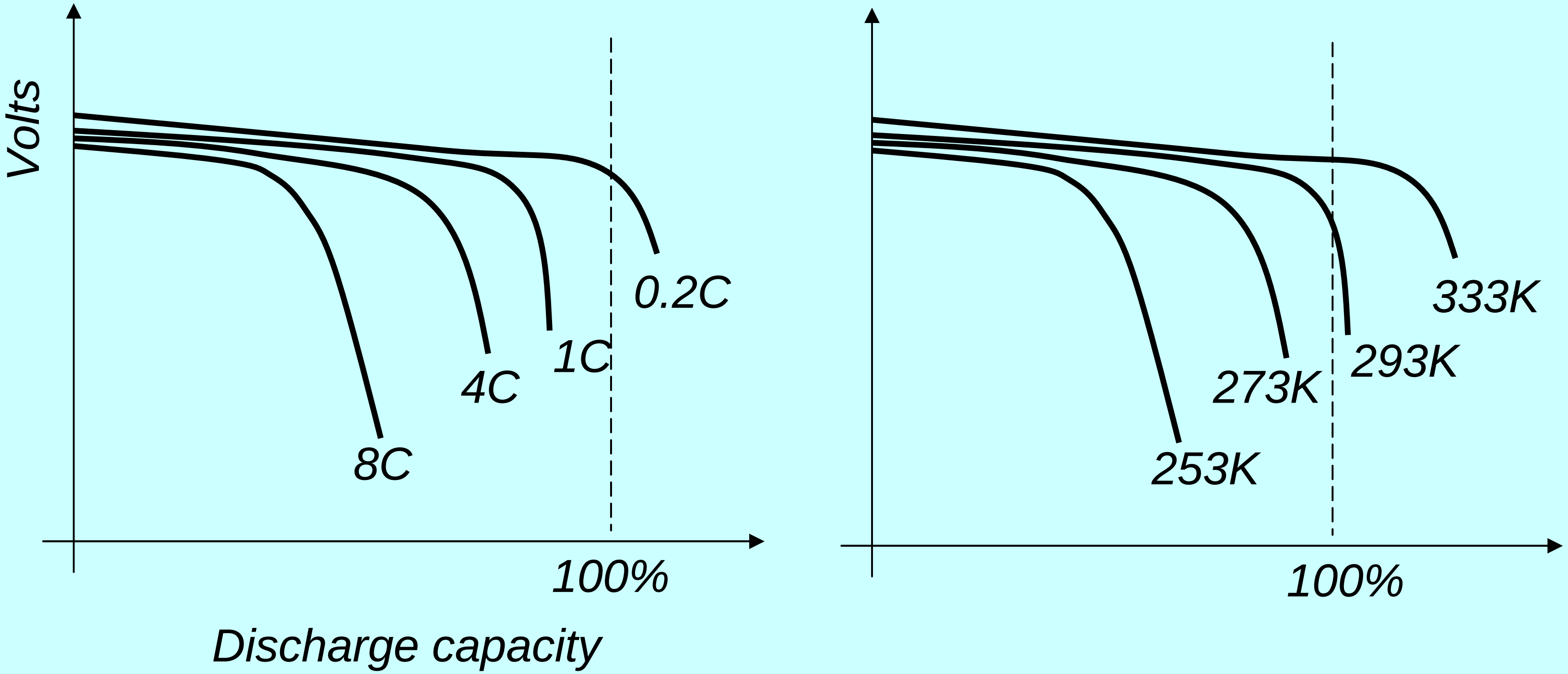


electrolyte bath: 35% sulfuric acid solution saturated with $PbS0_4$

Theoretical limit of lead-acid energy density: 0.58MJ/kg

Berndt, p. 36, 43

Overall Discharge Dependence on Current and Temperature



Nominal discharge rate C is capacity of battery in Ah, divided by one hour (typical).

Some variation of shapes among battery technologies, e.g., lithium lines more sloped.

Osaka & Datta, p. 30, 61, 63

Image removed for copyright reasons.

Please see: Rutherford, K., and D. Doerffel. “Performance of Lithium-Polymer Cells at High Hydrostatic Pressure.” *Proc. Unmanned Untethered Submersible Technology*, 2005.

Lithium-polymer cells: charge/discharge characteristic

From Rutherford & Doerffel

Comparison of Battery Performance for Mobile Applications

	Energy density, MJ/kg, MJ/l	Memory effect	Maximum current	Recharge efficiency	Self-discharge, %/month at 293K
Lead-acid	**0.14, 0.36**	**No**	**20C**	**0.8-0.94**	**??**
Ni-Cd	**0.24, 0.72**	**Yes**	**3C**	**0.7-0.85**	**25**
NiMH	**0.29, 1.08**	**Yes**	**0.6C**		**<20**
Li-ion	**0.43-0.72, 1.03-1.37***	**No**	**2C**		**12**

All have 300+ cycles if max current is not exceeded.

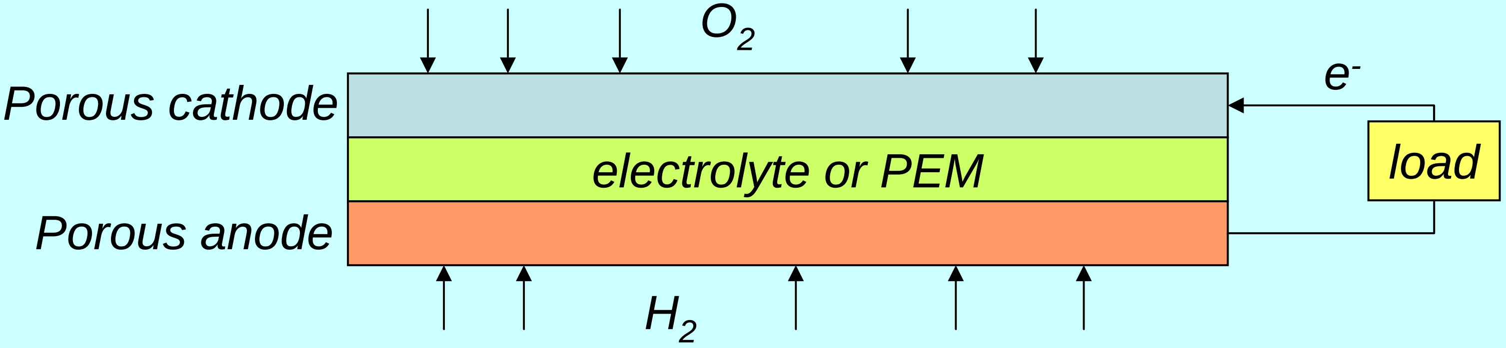
** Lithium <u>primary</u> cells can reach 2.90 MJ/l*

Osaka & Datta, p. 41, 449; Berndt p. 254

Fuel Cells

- Electrochemical conversion like a battery, but the fuel cell is defined as having a *continuous supply of fuel*.
- At anode, electrons are released: $2H_2 \rightarrow 4H^+ + 4e^-$
- At cathode, electrons are absorbed:

  $O_2 + 4e^- + 4H^+ \rightarrow 2H_20$
- Proton-exchange membrane (PEM) between electrodes allows H^+ to pass, forcing the electrons around outside the battery – the load. PEMFC operates at 300-370K; a low-temperature fuel cell. ~40% efficient.



Larminie & Dicks

Some Fuel Cell Issues

- High sensitivity to impurities: e.g., PEMFC is permanently poisoned by 1ppb sulfide.
- Weight cost of storage of H_2 in metal hydrides is 66:1; as compressed gas: 16:1.
- Oxidant storage: as low as 0.25:1
- Reformation of H_2 from other fuels is complex and weight inefficient: e.g., Genesis 20L Reformer supplies H_2 at ~ 0.05 kW/kg
- Ability of FC to change load rapidly.
- ***Typical Overall Performance Today:***

  0.025 kW/kg, 0.016 kW/l

Larminie & Dicks, ch. 8, Griffiths et al.

State of the Art 2005

- Gas turbines for large naval vessels due to extremely high power density, and the high thermal energy content of traditional fuels. But also used for <1kW sources, e.g., smart soldier
- Li-based batteries now available at ~0.65MJ/kg (180kWh/kg); gold standard in consumer electronics and in autonomous marine applications
- Fuel cells are still power-sparse and costly for most mobile applications, but continue to be developed. More suitable are power generation plants in remote locations.

References

- Pulkrabek, W.W. 2004. Engineering fundamentals of the internal combustion engine. Upper Saddle River, NJ: Pearson Prentice-Hall.
- Osaka, T. and M. Datta, eds. 2000. Energy storage systems for electronics. Amsterdam: Gordon and Breach.
- Baumeister, T., E.A. Avallone, and T. Baumeister III, eds. 1987. Marks' Standard Handbook for Mechanical Engineers. New York: McGraw-Hill.
- Berndt, D., 1993. Maintenance-free batteries. New York: Wiley.
- Giampaolo, T. 1997. The gas turbine handbook: Principles and practices. Lilburn, GA: Fairmont Press.
- Dhameja, S. 2001. Electric vehicle battery systems. Boston: Newnes.
- Larminie, J. and A. Dicks 2003. Fuel cell systems explained. West Sussex, UK: Wiley.
- Thring, R.H., ed. 2004. Fuel cells for automotive applications. New York: ASME Press.
- Boonstra, H., G. Wuersig, and K.O. Skjolsvik 2005. "Fuel Cell Technology in Ships: Potential Applications in Different Market Segments and a Roadmap for Further Developments." Proc. Marine Science and Technology for Environmental Sustainability (ENSUS).
- Rutherford, K. and D. Doerffel 2005. "Performance of Lithium-Polymer Cells at High Hydrostatic Pressure." Proc. Unmanned Untethered Submersible Technology.
- Griffiths, G., D. Reece, P. Blackmore, M. Lain, S. Mitchell, and J. Jamieson 2005. "Modeling Hybrid Energy Systems for Use in AUV's" Proc. Unmanned Untethered Submersible Technology.