Watts to Wheels

-or-

Why Your 'Bot Needs More Juice

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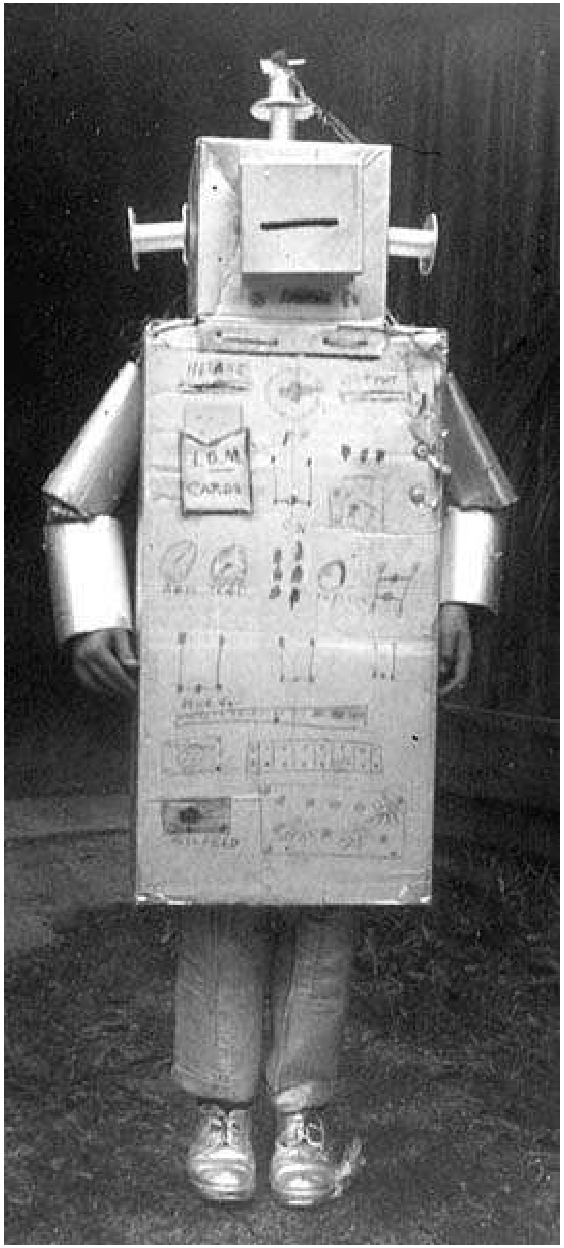
2004 Trinity College Fire Fighting Home Robot Contest

Who Am I?

- **Nisley: It's "Niss-lee"**
- **Above the Ground Plane**
  - **Circuit Cellar magazine**
    - **www.circuitcellar.com**
  - **Analog & RF stuff**
  - **This talk & more: June 2004**
- **Embedded Space**
  - **Dr. Dobb's Journal magazine**
    - **www.ddj.com**
  - **All about embedded systems**
- **The usual diversions**
  - **Recumbent radio**
  - **Home repair**

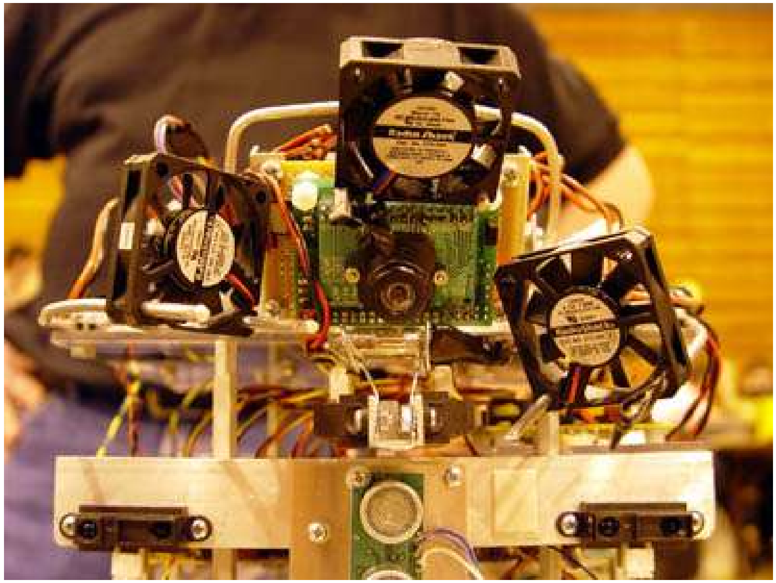


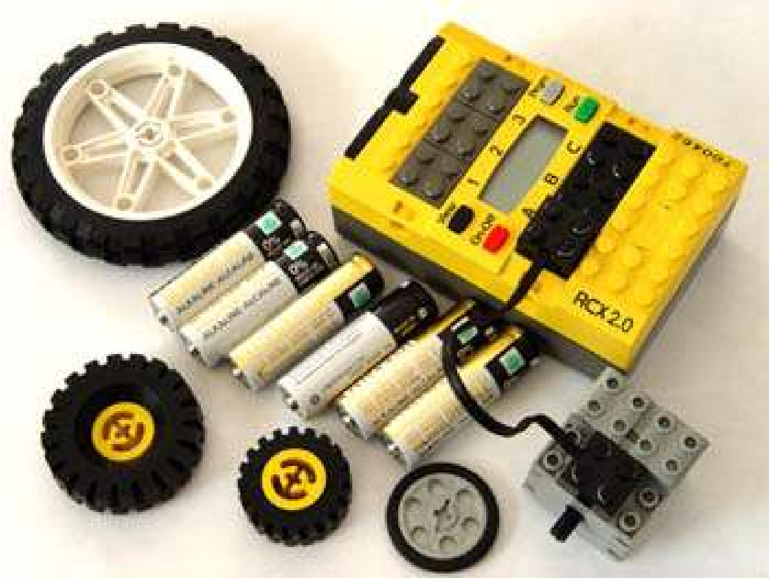
Design Strategies

- Performance first?
  - Can't fit the motor
  - Can't tote the battery
- Hardware first?
  - See what happens
- Cost first?
  - Performance counts
- Iterative design?
  - Better start early
- You need numbers…
  - Physics!

Why Are We Here?

- **Power!**
  - **... how many watts?**
- **Linear Kinematics**
  - $s = s_0 + v_0 t + at^2/2$
  - **The rest is easy!**
- **Dynamics**
  - **Force ➡** $F = m \times a$
  - **Traction ➡** $\mu = F/F_n$
- **Torque ➡** $\tau = s \times F$
- **Motors & Gearing**
- **Why Things Go Wrong**
- **Freebies!**





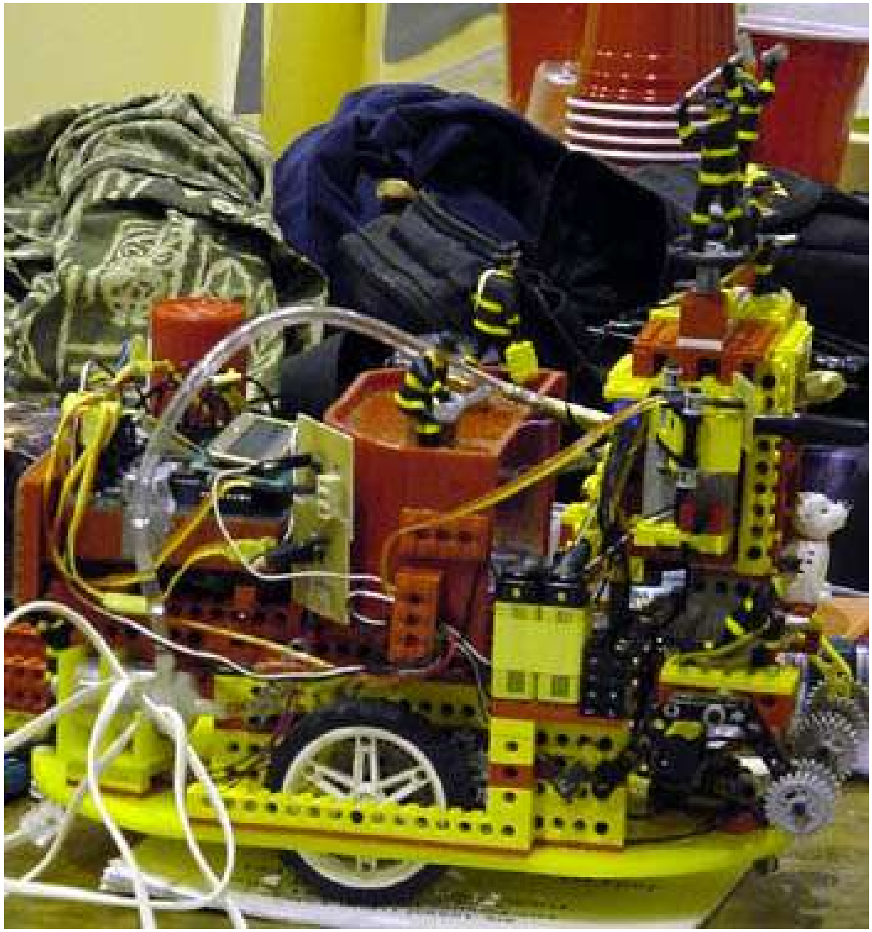
Linear Kinematics

- **One-dimensional**
  - **s = distance**
    - **meters**
  - **v = velocity (speed)**
    - **meters/sec**
  - **a = acceleration**
    - **meters/sec/sec = m/s^2**
- **$s=s_0+v_0t+at^2/2$**
  - **set ruler: $s_0=0$**
  - **at rest: $v_0=0$**
- **$s=at^2/2$**
  - **It's that simple...**

The obligatory faked photo...

Useful Equations

- $s = t \times (v_0 + v)/2$
  - **Measure:** v & s ➡ t
    - $t = 2s/(v_0 + v)$
- $v^2 = v_0^2 + 2a(s - s_0)$
  - **Specs:** s & a ➡ v
    - $v = \sqrt{(2a(s - s_0))}$
  - **Measure:** s & v ➡ a
    - $a = v^2/2(s - s_0)$
- $s = at^2/2$
  - **Specs:** s & a ➡ t
    - $t = \sqrt{(2s/a)}$
  - **Measure:** s & t ➡ a
    - $a = s/(t^2/2)$

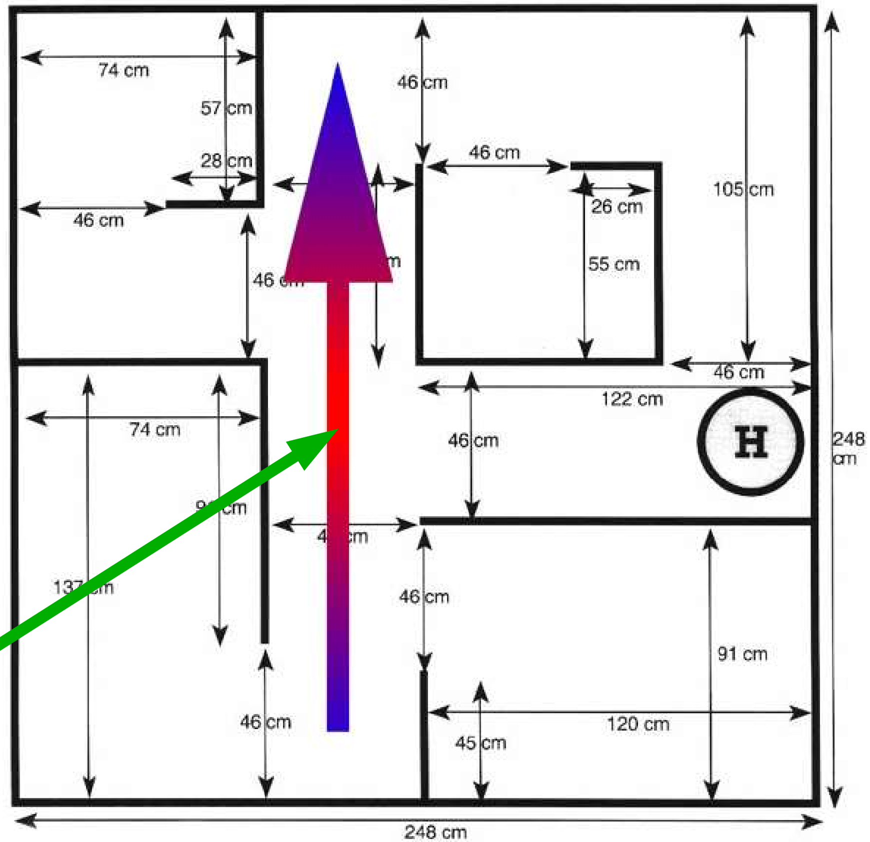


Kinematics says:

Assume your 'bot is a point...

Performance!

- **Set a Spec…**
  - **Distance = s = 2 m**
  - **Time = t = 1 s**
  - **But accel 1 m, decel 1 m**
    - **s=1 m & t=0.5 s**
- **s & t ➡ a**
  - **$a = s/(t^2/2) = 8\ m/s^2$**
    - **$1\ G = 9.8\ m/s^2$…**
- **a & s ➡ v**
  - **$v = \sqrt{(2as)} = 4\ m/s$**
    - **14 km/h = 9 mph = 13 f/s**
- **This is aggressive…**

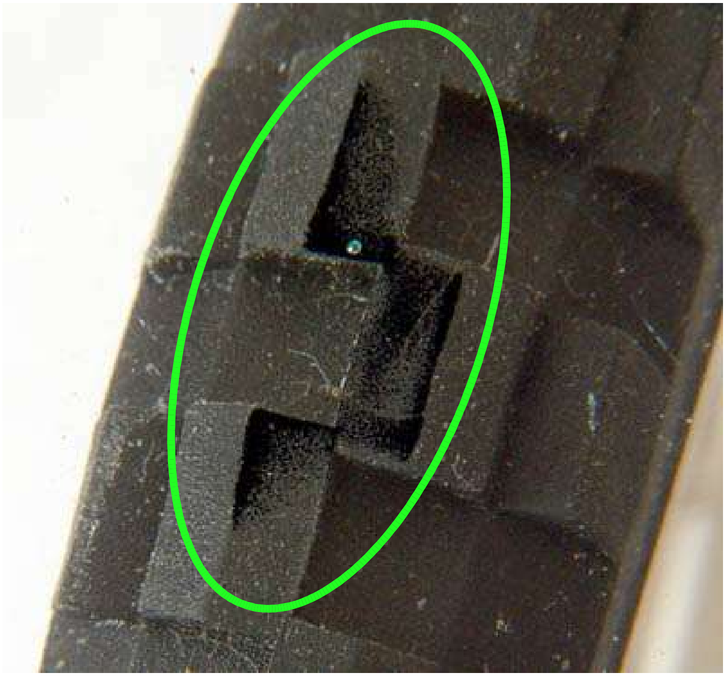


Dynamics

- $F = m \times a$ = m(dv/dt)
  - Want change in v? ➡ a
  - Have constant a? ➡ $F \propto m$
- Say robot weighs 1 kgf
  - *not* 1 kg, except on Earth
  - 1 kgf = 9.8 N = 2.2 lb
- $F = 1\ kg \times 8\ m/s^2 = 8\ N$
  - 8 N = 0.8 kgf = 1.8 lb
- Force requires friction
  - Floor is flat, not cleated
  - Skid marks are bad form
  - How to measure friction?

Coefficient of Friction

- **Contact Patch**
  - **Tire compound**
  - **Robot weight (aka mass)**
    - **Photos ➡ 0.5 kgf on 1 tire**
- **$\mu = F/F_n$ = pull/weight**
  - **Does *not* depend on area!**
    - **Ideally, that is…**
- **Easy to measure**
  - **Brake or lock wheels**
  - **Drag with weight scale**
  - **Weigh ‘bot in same units**
- **Answer: $\mu = 0.90$**
  - **Hard = less, soft = more**

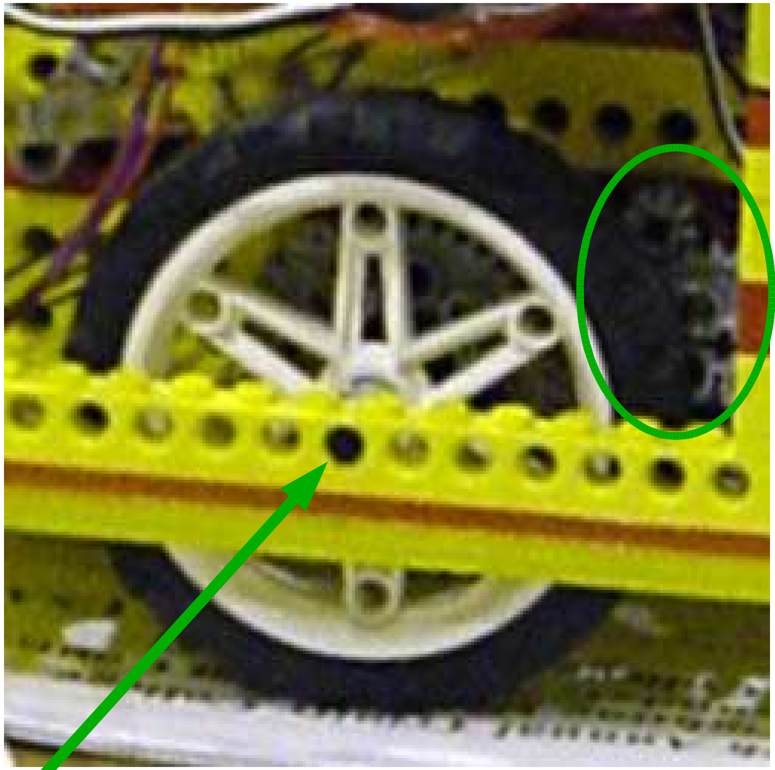


Traction Limit

- **Acceleration too high?**
  - **Lego? No problem!**
  - **Wild spec? *Rrrmm*...**
- **Traction needs weight**
  - **Traction ≤ μ×Weight**
  - **Weight = 8N/0.9 = 8.9 N**
    - **8.9 N = 0.9 kgf = 2 lb**
    - ***Very* close to 1 kgf spec!**
- **Traction ➡ accel limit**
  - **If you're close...**
  - **...other problems!**
- **How to get force?**
  - **Motors produce torque...**

Torque

- **Twist around an axis**
- **$\tau = s \times F$**
  - **s = distance: axis to force**
  - **F ≤ friction limit**
  - **Unit = meter-newton**
    - **newton-meter? *Bah!***
    - **Not the same as energy!**
- **$\tau = 0.041\text{m} \times 8\text{N}$**
  - **Need 0.33 m•N for 0.5 s**
- **Lego 4mm plastic shaft**
  - **$F = \tau/s = 0.33\text{m•N}/0.002\text{m}$**
    - **164 N = 37 lbf**
    - **Anybody see a problem?**

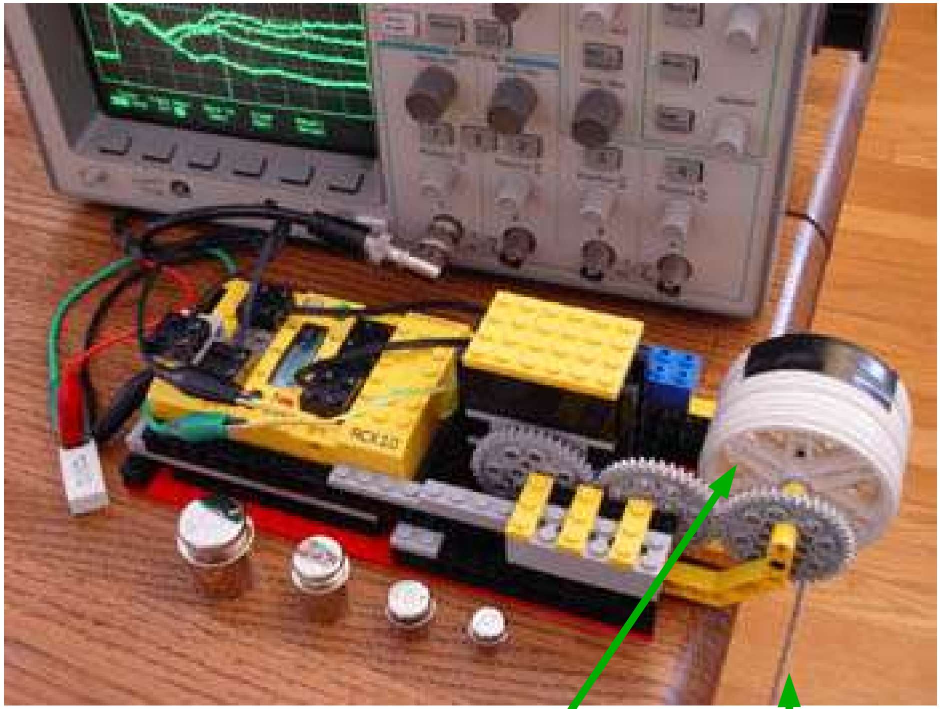


Lego tire is 81.6x15 mm
Radius = 81.6/2 = 0.041 m

Lego shaft diameter is 4 mm
Radius = 0.002 m

Motor Torque

- **Lego Dynamometer**
  - $\tau = s \times F$
    - s = radius of wheel
    - F = weight in kgf or gf
  - **Usual assumptions**
    - Weightless, frictionless
    - Inertialess rotation…
- **Lift = 120gf max**
  - $\tau = 0.033\text{m} \times 1.1\text{N}$
  - $\tau = 0.\underline{0}36\ \text{m}\bullet\text{N}$
  - We need $0.\underline{3}3\ \text{m}\bullet\text{N}$
    - Anybody see a problem?
- **Inclined planes**
  - Gravity dilution: $\sin(\Theta)$



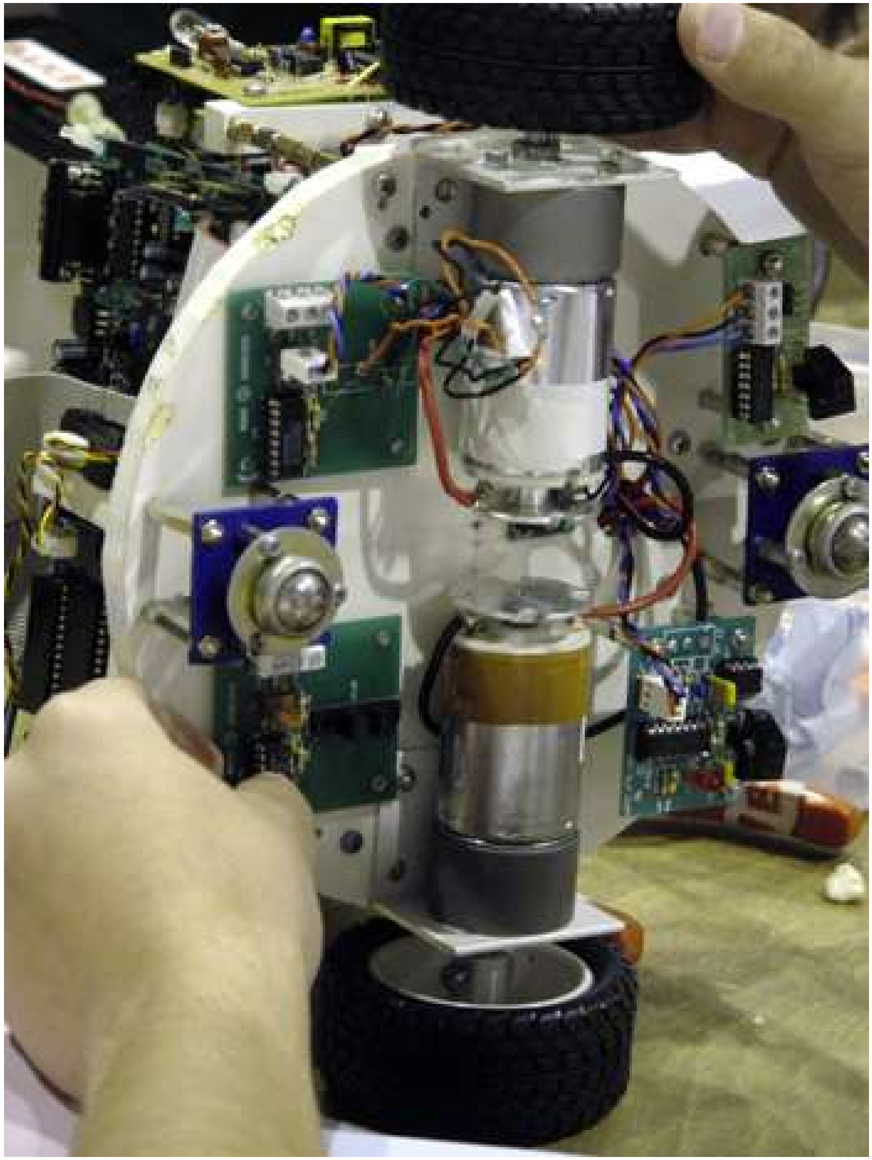
Wheel radius = 33mm

Weight = 0.120 kgf x 9.8 N/kgf = 1.1N

Nice Lego motor survey at
http://www.philohome.com/motors/motorcomp.htm
finds stall torque = 0.06 m•N

Homework Hints

- **Measure motor torque**
  - **Get the units right!**
- **Torque ➡ Force**
  - **Use correct distance**
- **Force ➡ Acceleration**
  - **Verify traction (hah!)**
- **Acceleration ➡**
  - **Speed**
  - **Time**
  - **Distance**
- **… ➡ *Performance***
  - **Now: fix your ‘bot!**

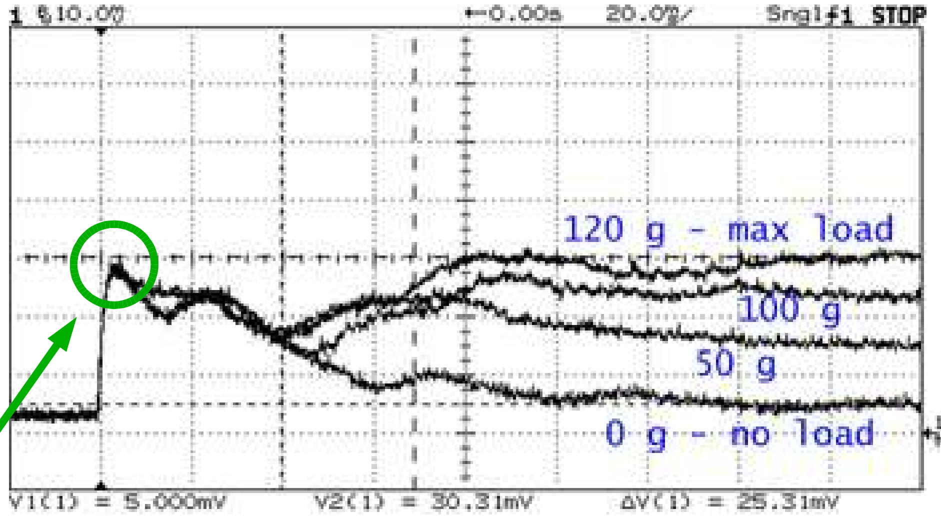


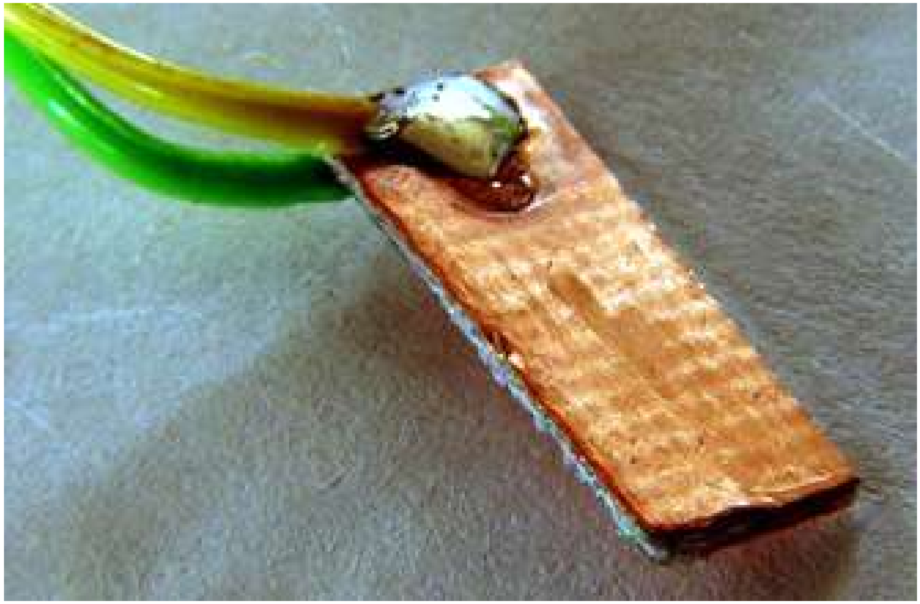
Gearing

- **Torque $\tau = s \times F$**
  - **Big s = low F = low a**
  - **Small s = high F = low v**
  - **Tradeoff: speed vs accel**
- **Speed in gear train**
  - **(rpm×teeth) = constant**
    - **Bigger gears go slower**
    - **Smaller gears push harder**
    - **Plastic breaks & wears out**
- **Power ∝ (rpm × torque)**
  - **Mind your units!**
  - **Pay attention to losses**
  - **Strength of materials**

Motor Current

- **Current ∝ load**
  - **∝torque ∝force ∝accel**
  - **High accel ➡ amps!**
- **Simple current probe**
  - **DVM is OK for DC load**
  - **Oscilloscope for peaks**
    - **Use 0.1Ω resistor ➡ V**
- **Losses everywhere**
  - **Resistance loss: V=IR**
- **Use heavy wires?**
  - **At least not Wire-Wrap**
  - **Measure voltage drops**
  - **Connectors? *Ugh!***





Motor Power

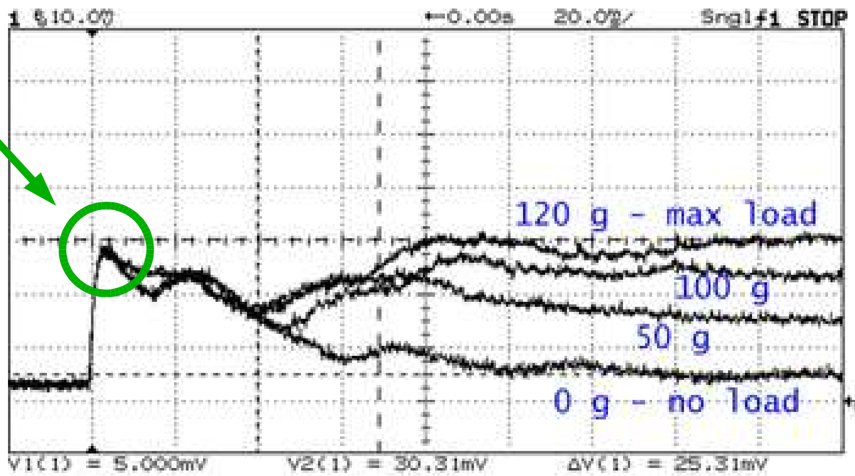
- **Watts = Volts × Amps**
  - **Amps ∝ load ∝ accel**
  - **Volts = batteries**
    - **Nominally constant, but...**
  - **Watts ∝ accel**
- ***Soooo...***
  - **Faster ‘bots = more watts**
  - **Lower watts = slower ‘bots**
- **Battery life = watt•hour**
  - **Or amp•hour**
  - **More watts ➡ fewer hours**
  - **Note max current limits**
    - **Li-polymer in particular**

1065 HP = 790 kW, 425 RPM

440 μHP
330 mW
340 RPM

Microcontroller Crashes

- **Peak current at start**
  - **Voltage drop = I×R**
  - **Start motor ➡ crash µC**

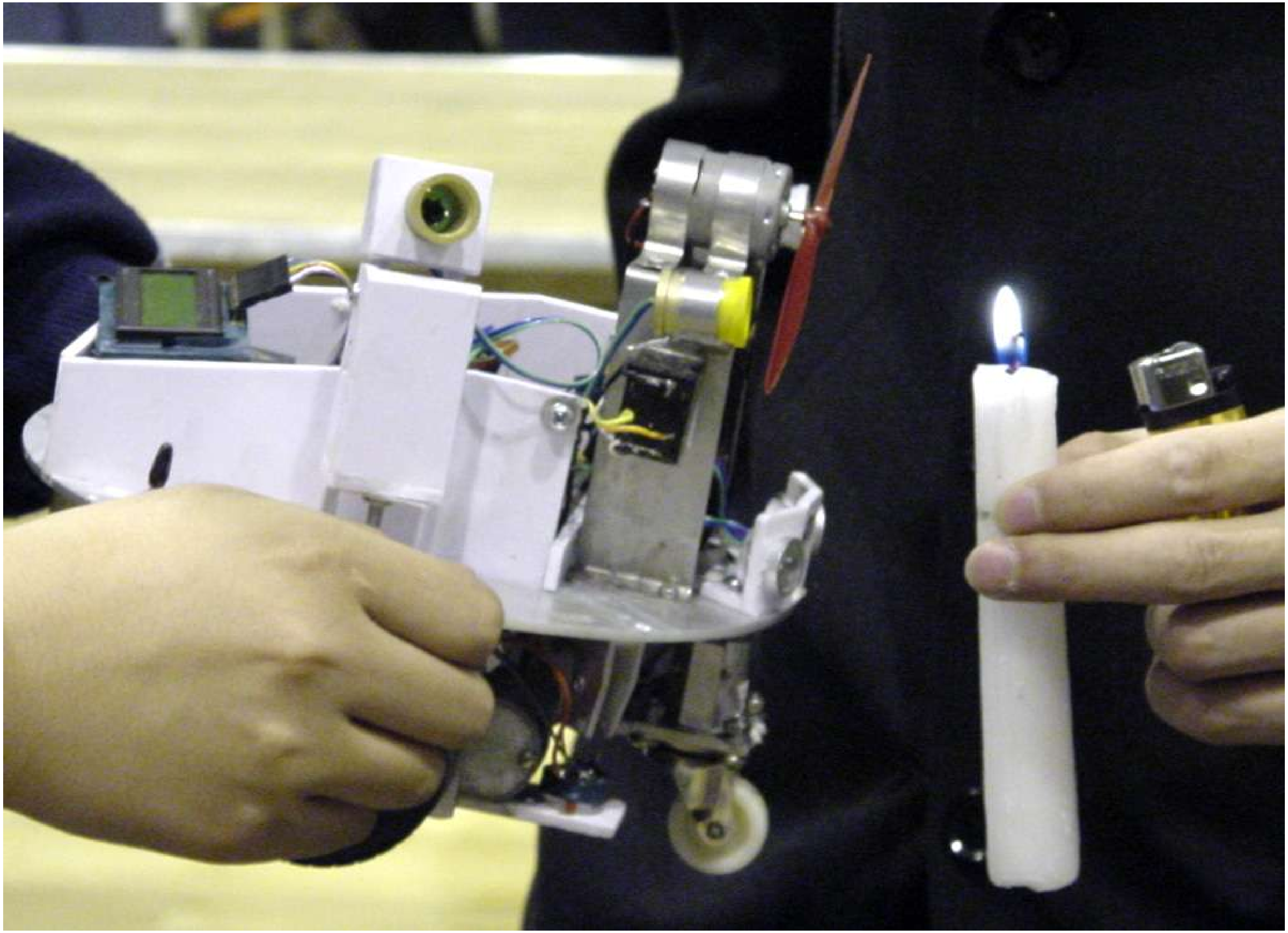


- **Brownout ➡ weirdness**
  - **Reduced margins**
  - **Low-voltage glitches**
  - **Commutation noise**
- **Always...**
  - **Separate motor wires**
  - **Separate "ground" wires**
  - **Relays are good**
    - **But lousy speed controls**
- **Measure!**

Homework Hints

- **Words To Live By…**
  - **Think Thrice**
  - **Measure Twice**
  - **Cut Once**
- **Use the Numbers**
  - **Even with guesses**
  - **Math helps you win**
- **Expect & Plan For…**
  - **Electrical noise**
  - **Extraneous IR**
  - **Dirt & Grit**
- ***Charge the Battery!***
- **Have fun…**

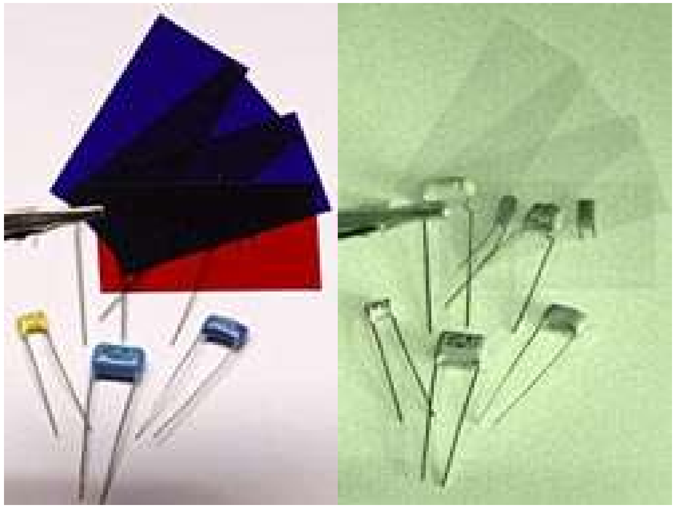
The End



But don't go away...

Freebies

- **Current probe resistor**
  - **100 mΩ ➡ 100 mV/A**
  - **7A continuous current (*hah!*)**
- **IR Filter material**
  - **My 2003 seminar has spectra**
  - **Use 3 blue + 1 red ➡ IR only**
  - ***Don't look at the sun!***
- **Slides as PDF ➡ diskette(!)**
  - **Also on Trinity website**
  - **OpenOffice on Linux/Win**
- **Not quite enough for all**
  - **If you're not going to use it, then don't grab it!**



The End

(really)