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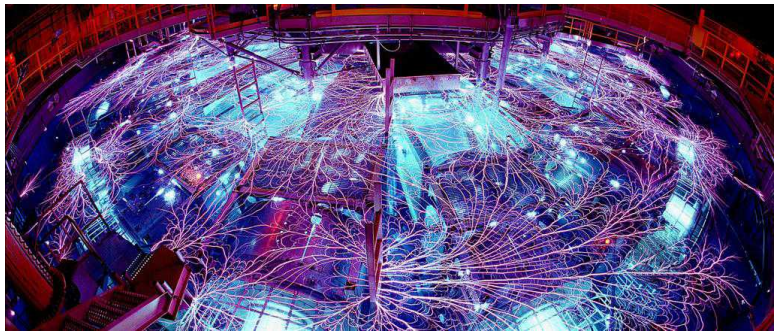

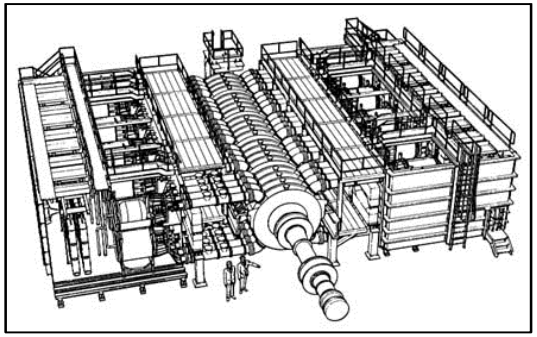

Pulsed Power: RLC Elements, Transmission Lines, and Marx Banks

Dr. William White

Z Pulsed Power Systems (01679)

20 January 2016

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Overview

- RLC Elements for Pulsed Power
- Transmission Lines for Pulsed Power
- Marx Banks
- Triggering of Marx Banks
- Applications of this Stuff!

Why Do Pulsed Power?

(Uhh… Besides Awesome Spaceship Battles?)

- Pulsed Power Squeezes Energy in Space and Time
- Lots of Applications Require "More"
  - Voltage
  - Current
  - Power

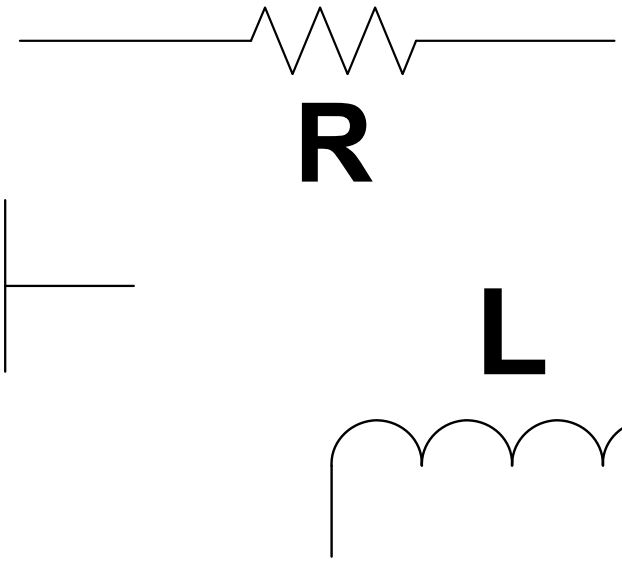
(All on Short Time Scales!)

- Examples…

X-ray Sources
High Energy Lasers
Microwave Sources
Fusion Experiments
Camera Flash Bulbs
High Energy Density Physics
Neutron Generators
Particle Accelerators
Electromagnetic Launchers
Laboratory Astrophysics

RLC Elements

- Resistors
  - Most Basic Element
  - Absorb Power
- Capacitors
  - Store Electrical Energy
- Inductors
  - Store Magnetic Energy
- Voltage and Current Sources Generate Energy
  - Batteries, Power Supplies
- Most Critical Elements for Pulsed Power (with Switches)



Ohm's Law and Power in Resistors

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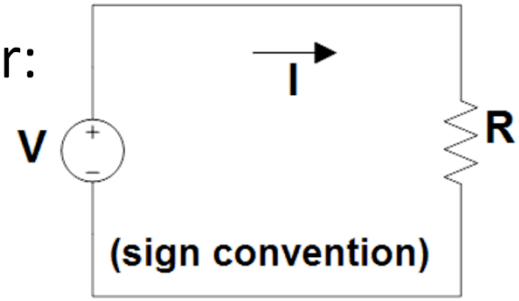
- How to Determine Current Flow in a Resistor:

$$V = I\,R$$

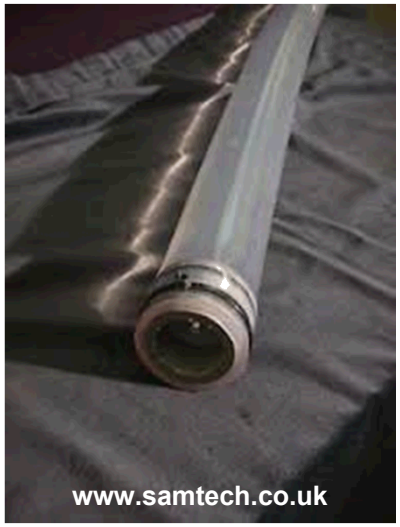


- Power Dissipated in a Resistor = Product of the Voltage and Current:

$$P = V\,I$$

$$P = I^2 \cdot R$$

$$P = \frac{V^2}{R}$$

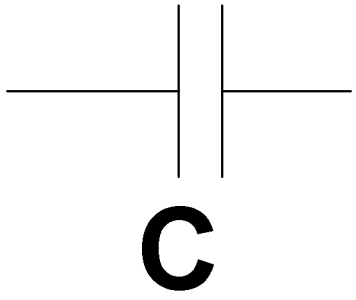


Note that by Sign Convention, P is Always > 0

(Resistors Always Absorb Power)

Capacitors

- A capacitor = two conductors separated by an Insulator
  - Capacitors Block DC
  - Capacitors Store Electrical Energy
  - Beware Voltage Reversals
  - Generally Higher Power than Batteries
  - Ideally Units have Pure Capacitance
    - Reality: Capacitors DO have Stray Inductances
    - Also Equivalent Series Resistance

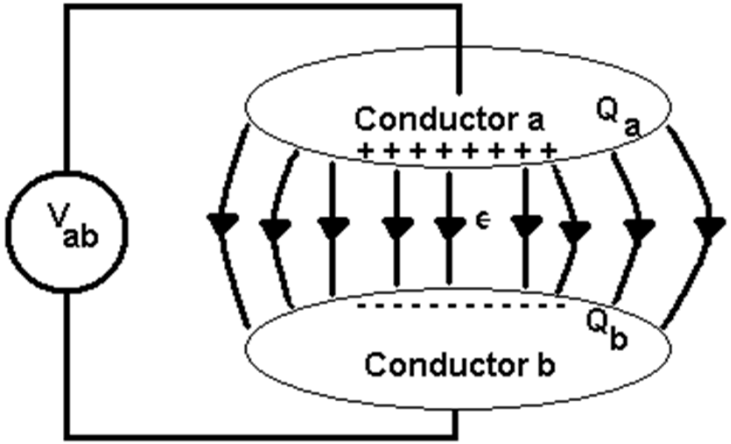


http://www.ga.com/series-cmx-self-healing-energy-storage-capacitors

Energy Storage in Capacitors

- Moving the Electric Charges onto the Plates Stores Energy

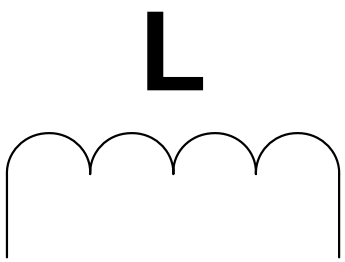
$$E_{cap} = \frac{1}{2} C \cdot V^2$$

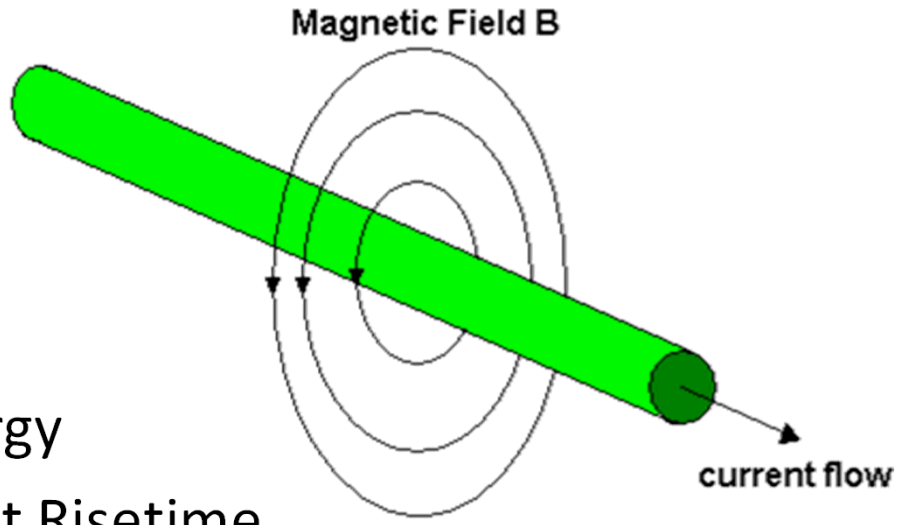


http://www.electrocube.com/product-categories/film-capacitors1/seacor-commodity-capacitors/

Inductors

- Current Flow in a Wire Loop Generates a Magnetic Field
  - To Change the Current, We Must Change the Magnetic Field Too…
  - A Voltage Develops: Inductance!



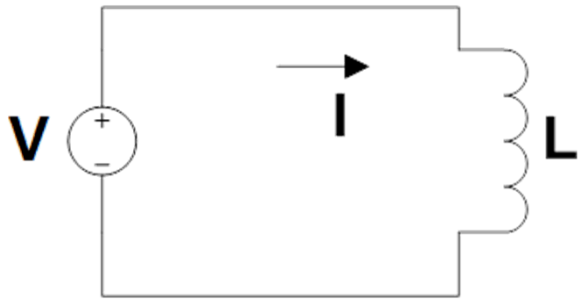


- Inductors Block AC
- Inductors Store Magnetic Energy
- Load Inductance Limits Current Risetime

Energy Storage in Inductors

- Building up Current Stores Energy
  - Analogously to Capacitors:

$$E_{ind} = \frac{1}{2} L \cdot I^2$$



Note: Inductors have Stray Capacitance Too!

Impedance of Inductors and Capacitors

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- Use Laplace/Fourier Transforms to Make ~Ohm's Law:

$$v(t) = L\frac{di(t)}{dt} \Rightarrow \mathbf{F}\{v(t)\} \Rightarrow V = (j\omega \cdot L)\cdot I$$

$$i(t) = C\frac{dv(t)}{dt} \Rightarrow \mathbf{F}\{i(t)\} \Rightarrow V = \left(\frac{1}{j\omega \cdot C}\right)\cdot I$$

Impedance → Each Term in the Parentheses *Looks* like a Resistance (with a Frequency Dependence)

V = Voltage

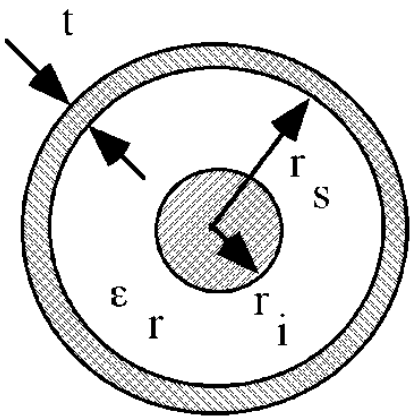
I = Current

ω = radian frequency

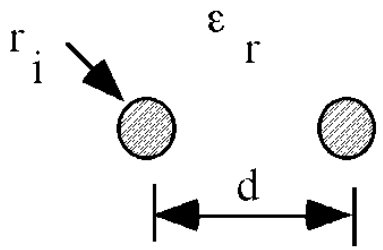
$j = \sqrt{-1}$

These are Still **Lossless** Components

Transmission Lines

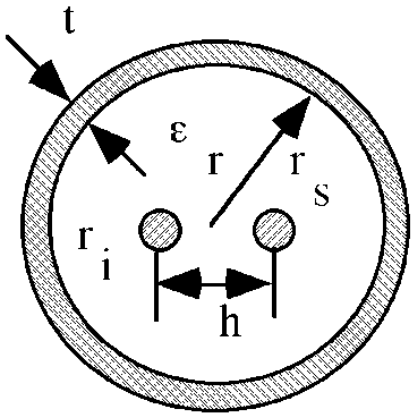


Coax

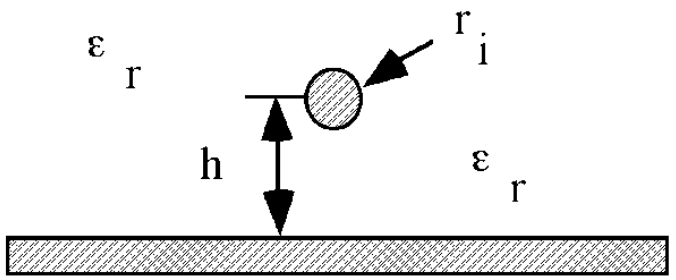


Parallel Conductors

(www.trantopcalc.sourceforge.net)



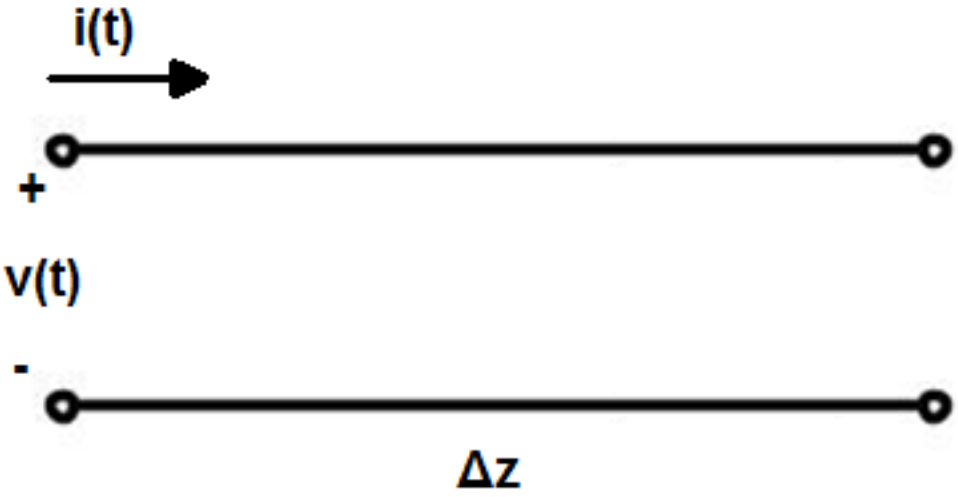
Balanced Shielded Line



Single Wire Near Ground

Transmission Lines

- Voltage and Current are Defined at a Time (t) and Place (z)
- Solve for the Voltage/Current at One Location in Terms of Another;
  - Take the Limit as $\Delta z \rightarrow 0$



Solve for:

$$\frac{v(t)}{i(t)} = Z_o$$

Impedance!

(Note: Impedance Z_o is not the same as distance z along the transmission line)

Lossless Transmission Lines

- Make a Simplifying Assumption (no losses)
  - Solve for **Impedance** and **Phase Velocity**:

$$\because Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}};$$

$$\because v_p = \frac{\omega}{\beta} = \frac{\partial z}{\partial t};$$

$$R, G = 0 \rightarrow$$

$$\beta \left(= \frac{2\pi}{\lambda} \right) = \omega\sqrt{LC} \rightarrow$$

$$Z_o = \sqrt{\frac{L}{C}}$$

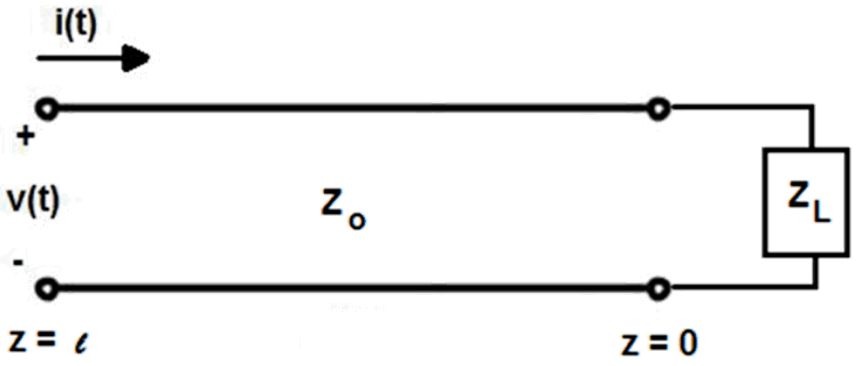
$$v_p = \frac{1}{\sqrt{LC}}$$

(Note: Impedance Z_o is not the same as distance z along the transmission line)

Length of Transmission Line Sets Pulsewidth!

Impedance Again?

- Impedance is a Characteristic of the EM Wave as Energy 'Flows' Down the Transmission Line
  - NOT a DC Resistance
  - Generally Dependent upon Frequency
- Changes in Impedance Generate Reflections
  - These are Required by the Boundary Conditions on the EM Wave
- Also Useful for Pulseshaping
- Matched Impedances → Maximum Power Flow



$Z_L << Z_o \Rightarrow$ Voltages cancel at the load

Negative reflected wave

$Z_L >> Z_o \Rightarrow$ Currents cancel at the load,

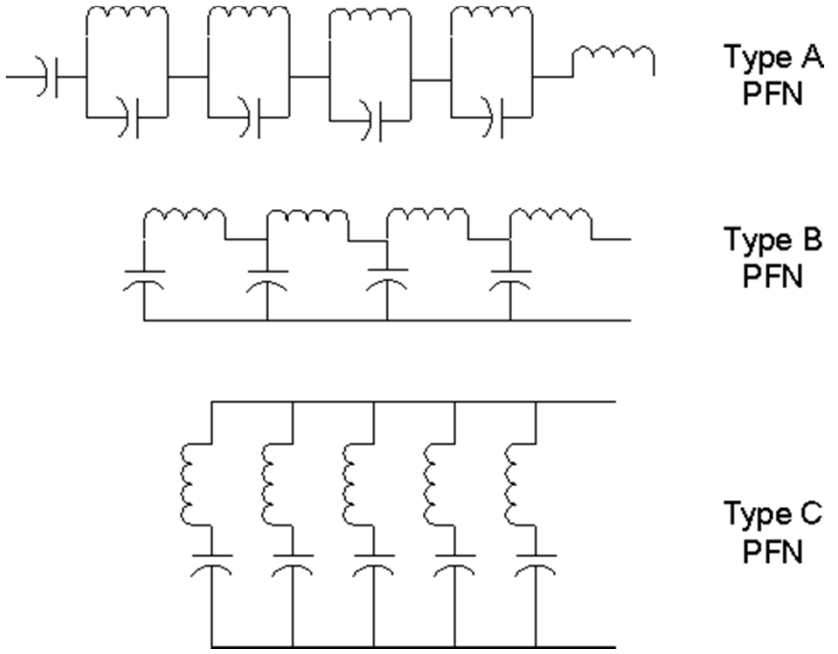
Positive reflected wave

$Z_L = Z_o \Rightarrow$ No apparent transition

No reflected wave!

RLC's and Transmission Lines

- For Pulsed Power these Concepts are Complementary
  - TLines are analyzed using RLC components (per unit length)
  - We Construct TLines from Discrete Components
  - We Use TLines to Approximate Discrete Components
  - We use TLine Models to Simulate Discrete Components
- Detailed Applications Drive Which Topology is Selected

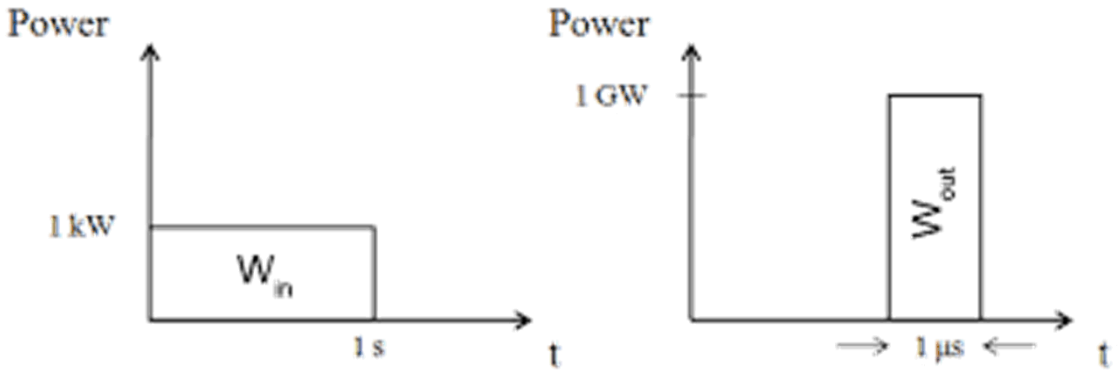


E.g.: Guillemin Equivalent Networks

Marx Banks

Marx Banks vs. Parallel Capacitor Banks

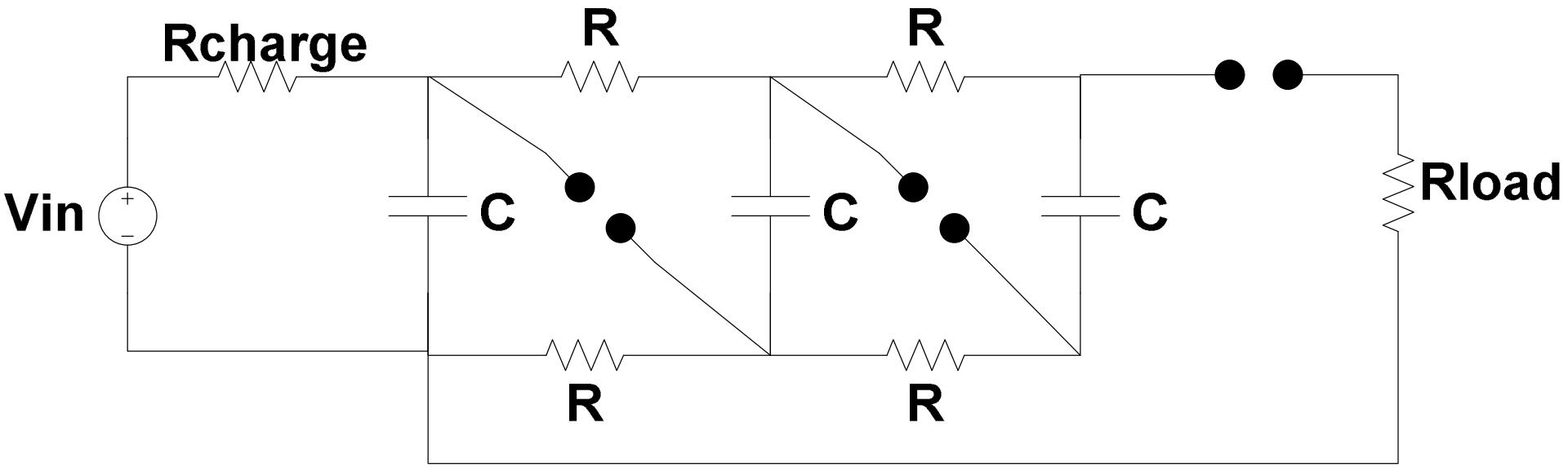
- Capacitor Banks Store Energy
- Marx Banks Store Energy AND Multiply the Voltage
- Marx Banks Charge Over Seconds, Discharge in Microseconds



No 5.4 MV Duracell's (Yet!)

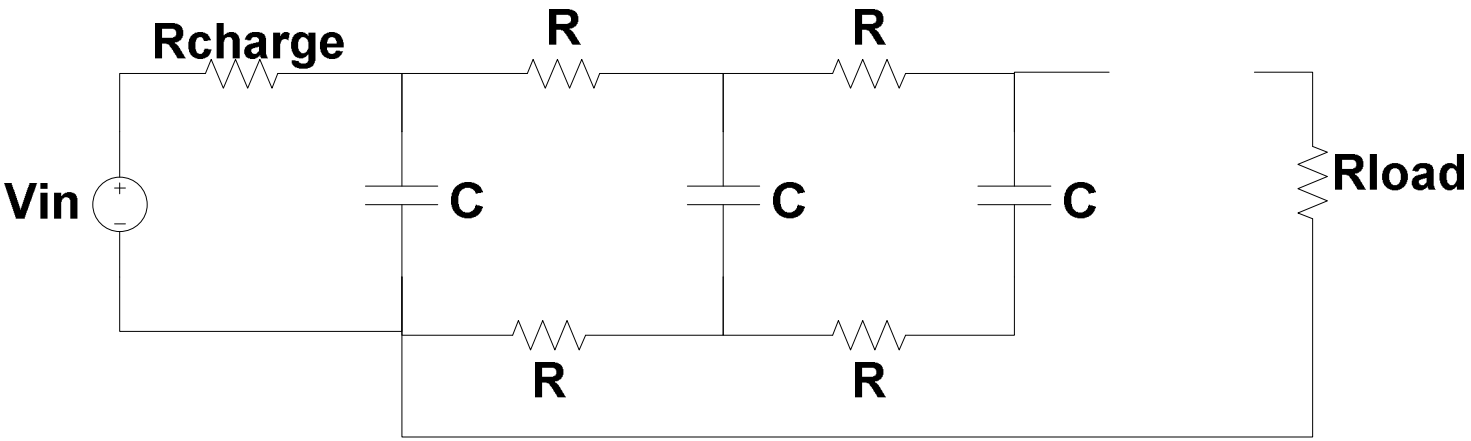
Basic Marx Bank

- Fast Switches Allow Parallel Charging
  - Discharge in Series

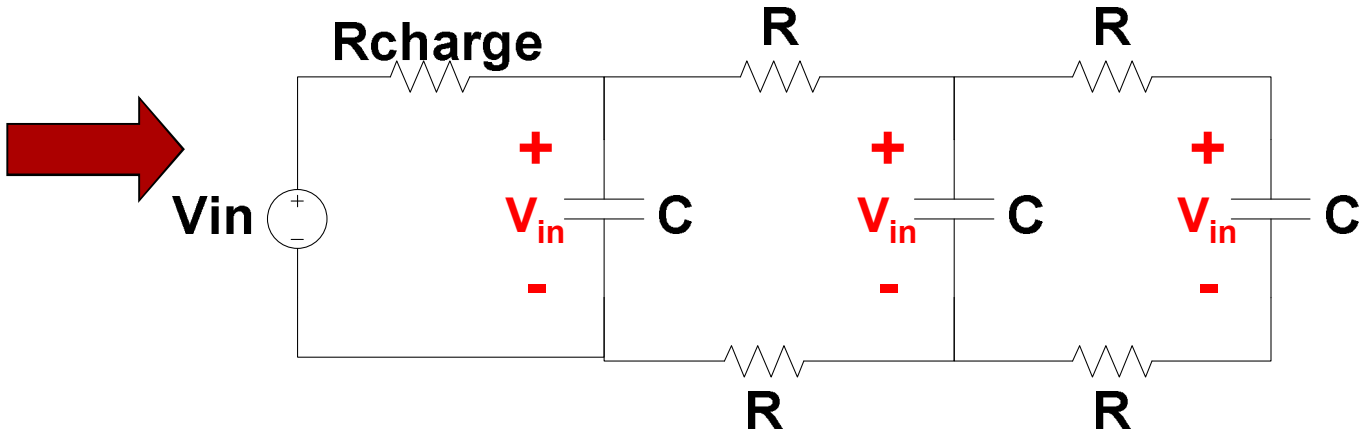


- Commonly Use Spark Gap Switches, Ignitrons
  - Novel Solid State Switches are Appearing!

Basic Marx Bank Analysis: Charging

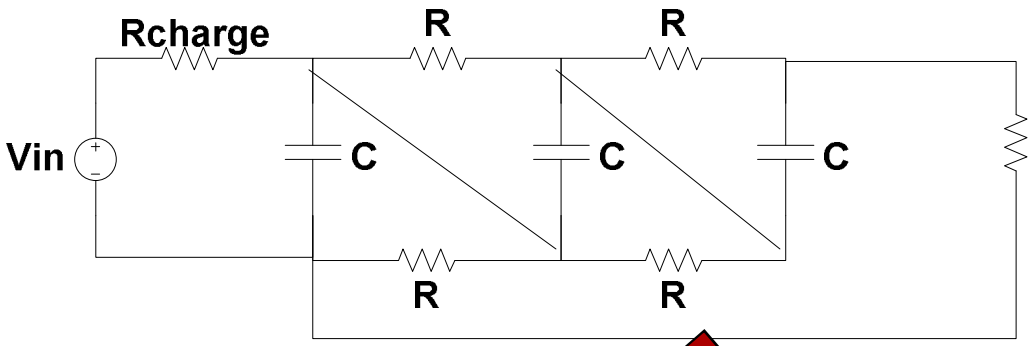


Since No Current Flows Through R_{load}, the Circuit can be Simplified



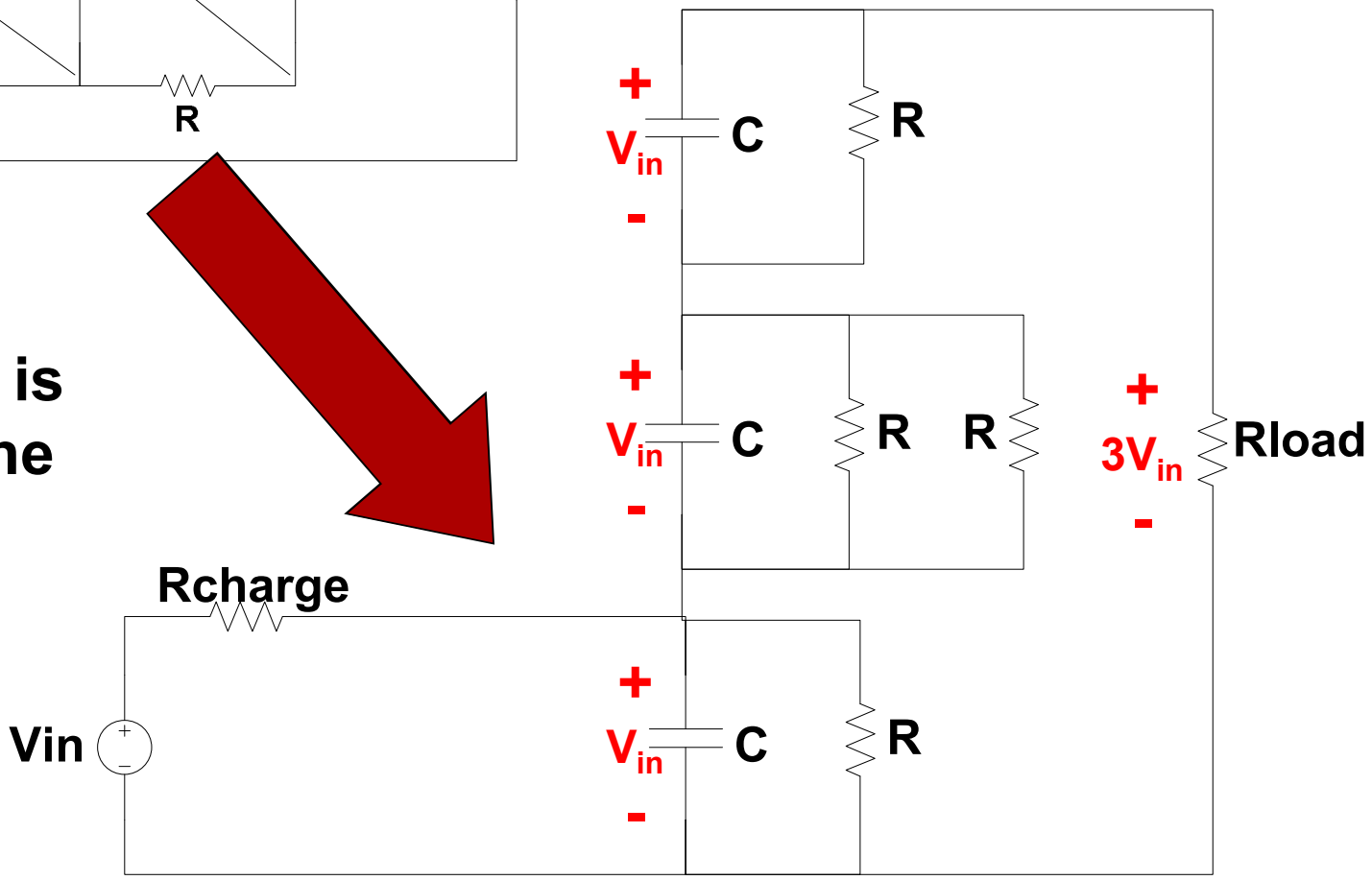
After "A Long Time"

Basic Marx Bank Analysis: Discharging



Redraw the Circuit:

Output Voltage is Multiplied by the Number of Stages!



Bipolar Marx Bank: Charging/Discharging

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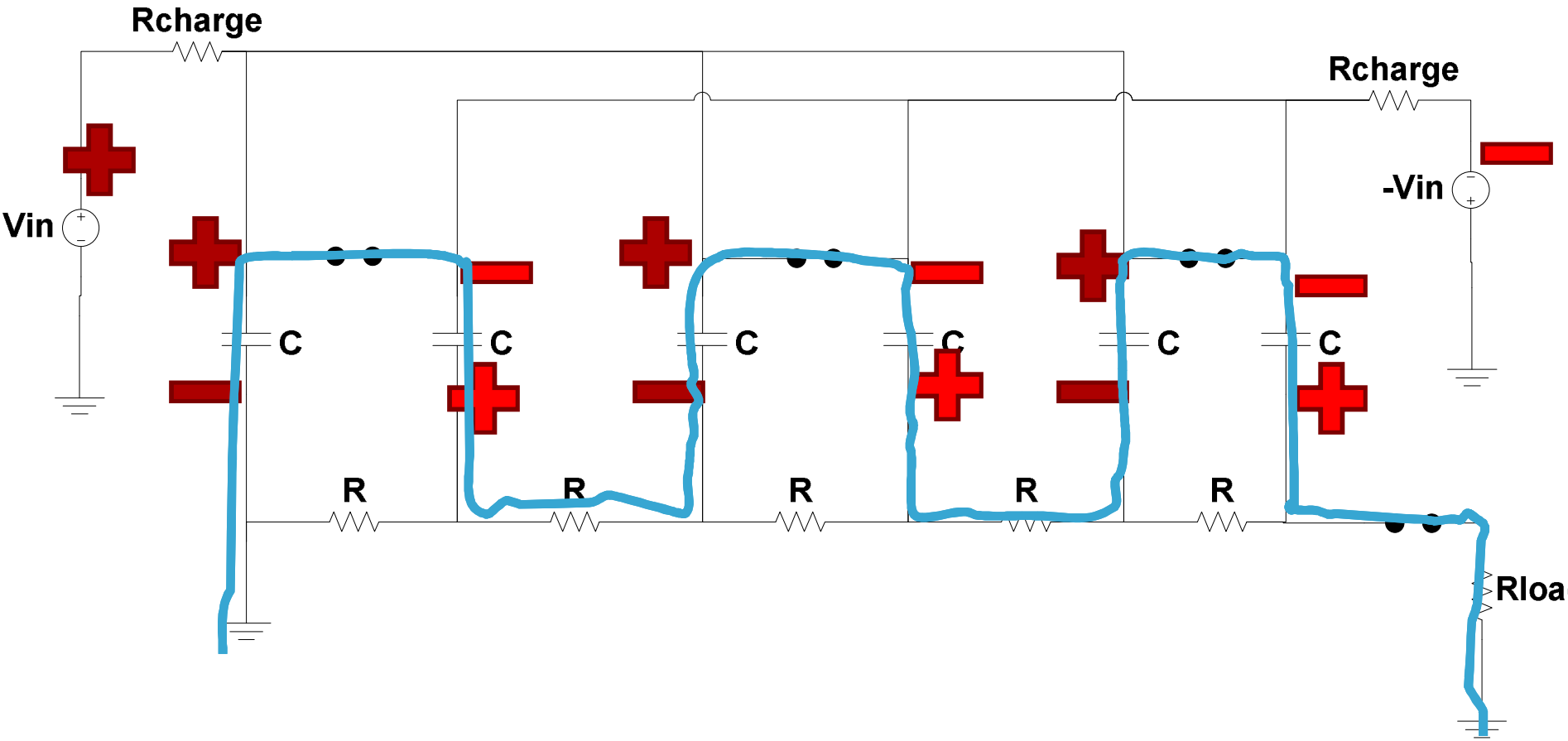

Z Main Marx Bank : Charging/Discharging

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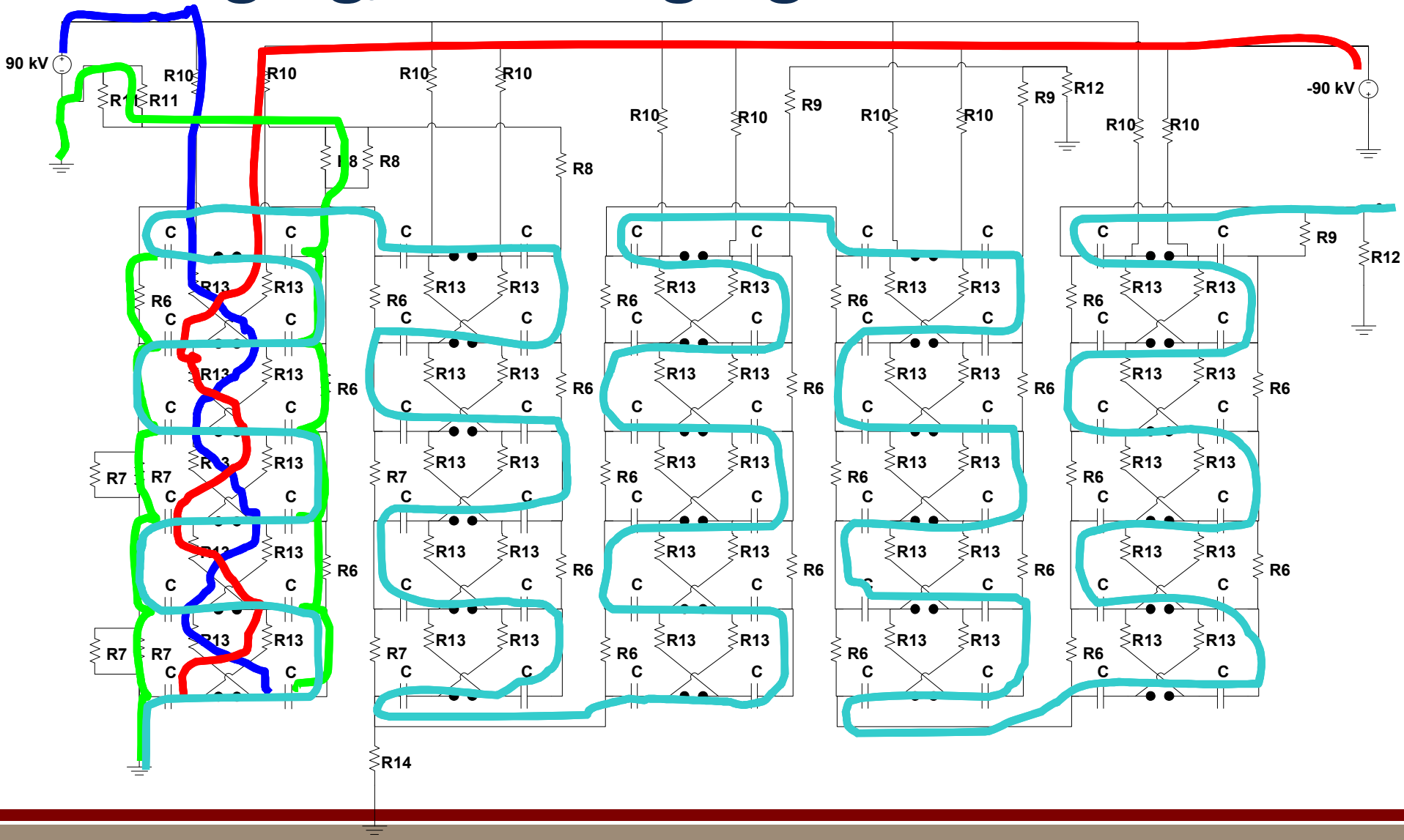
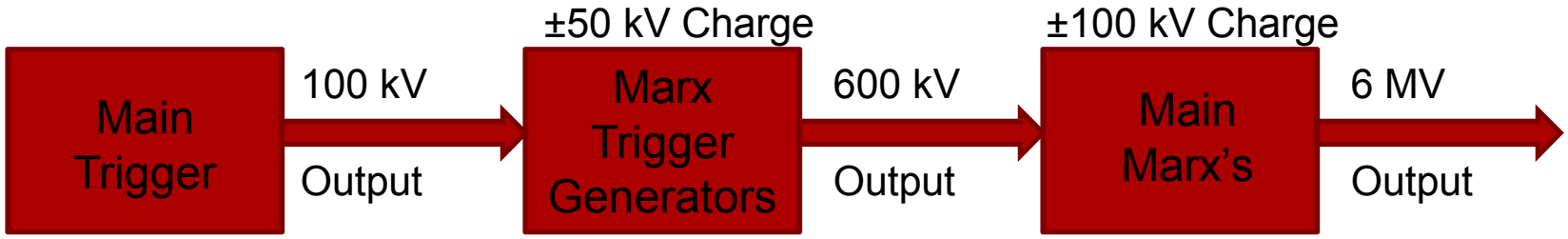


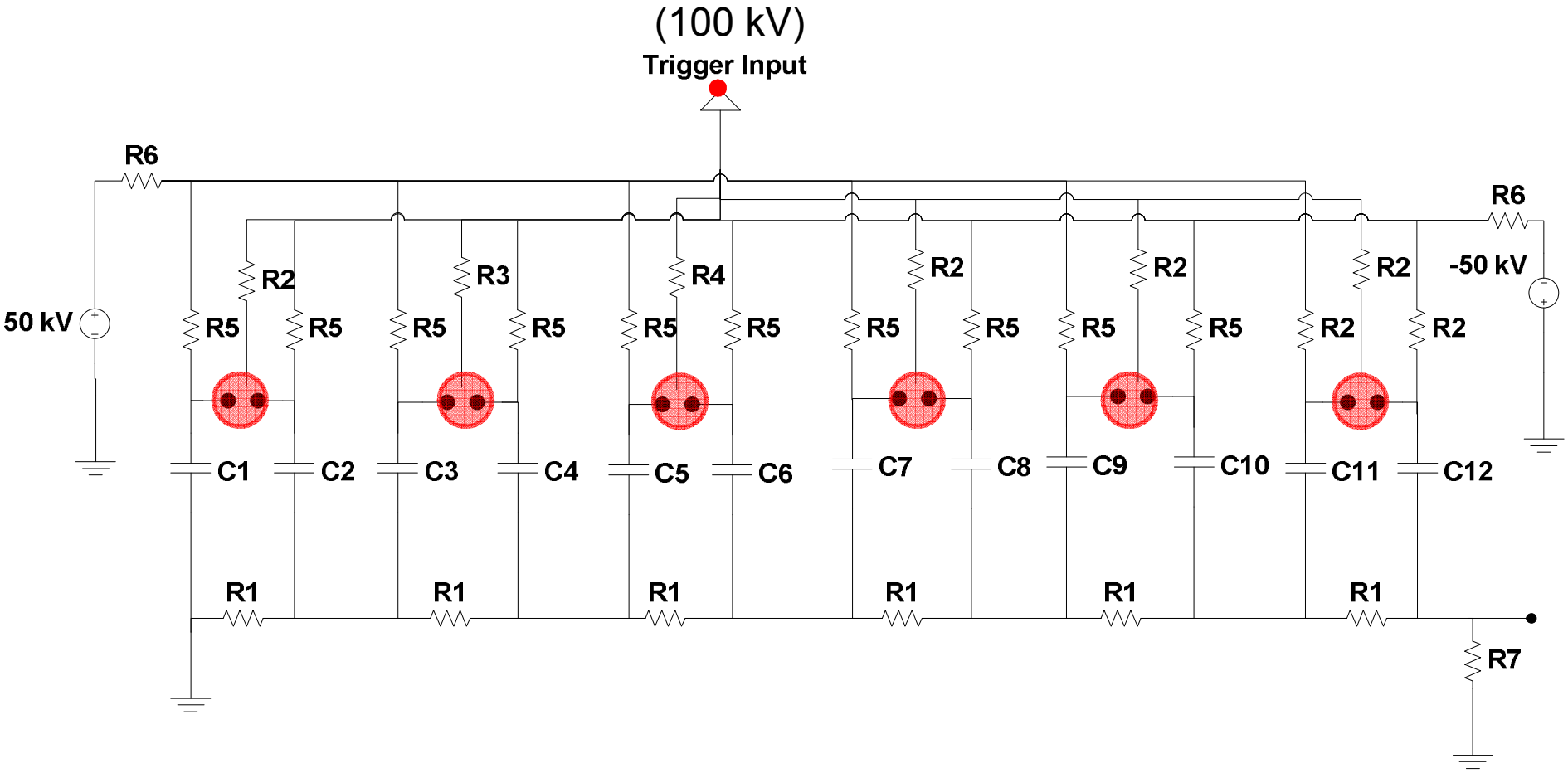
Triggering Marx Banks

- Triggers are Usually Staged
- In Many Systems, Each Switch has Dedicated Triggers
- Other Marx Banks Only Supply Triggers to Early Stages
- Those Stages Trigger Later Sections
  - **Reduced Jitter!**

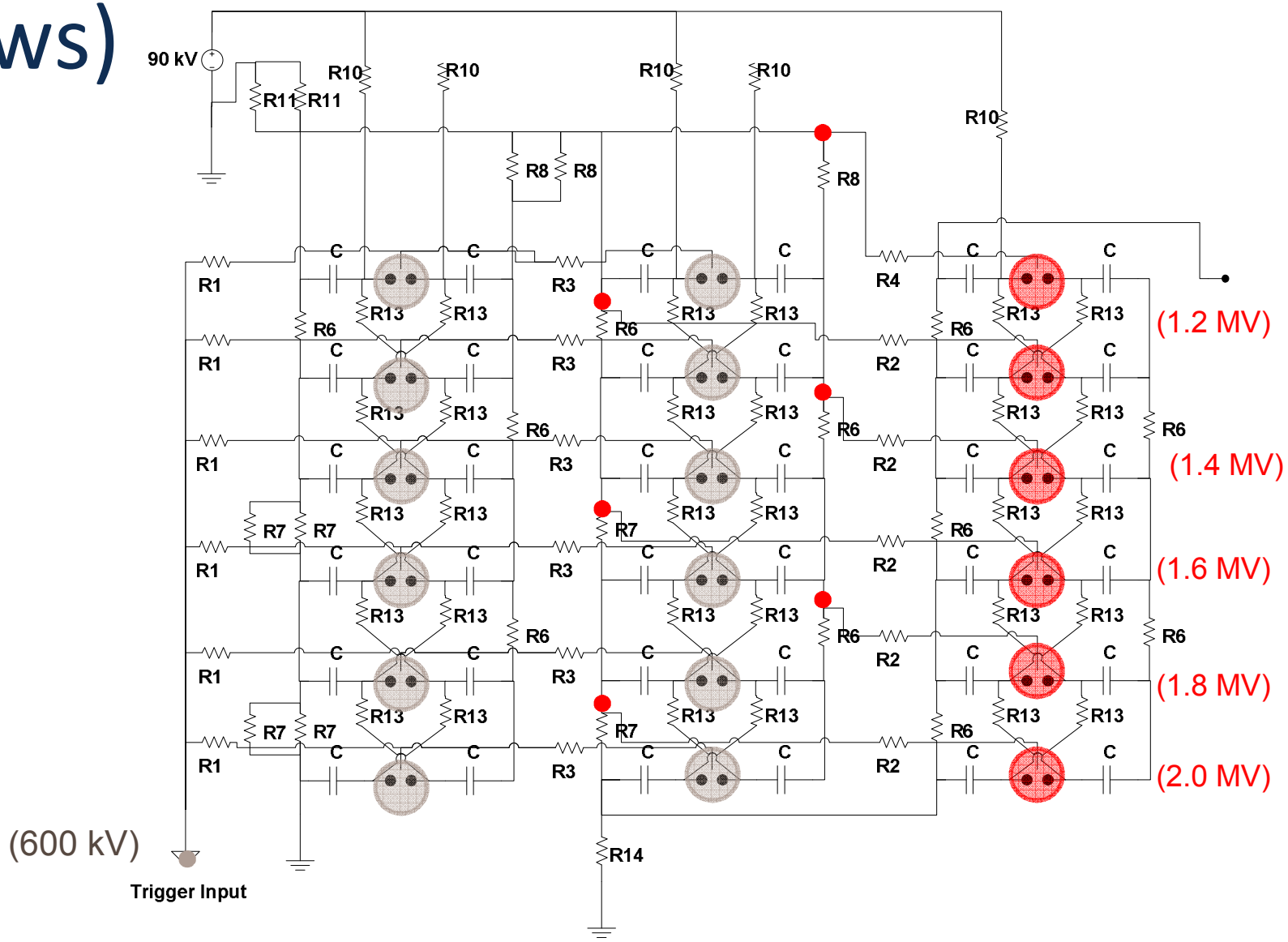


(Diagram of SNL Z Triggering)

Marx Triggering: All Switches Externally Triggered



Z Main Marx Triggering (First 3 Rows)



What Can We Do With All This?

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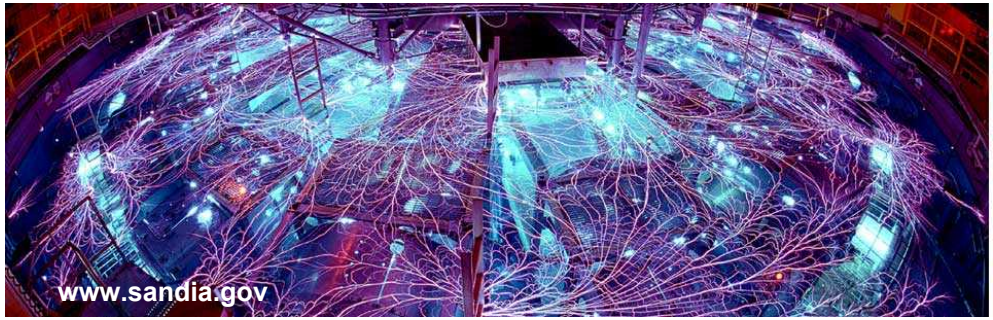
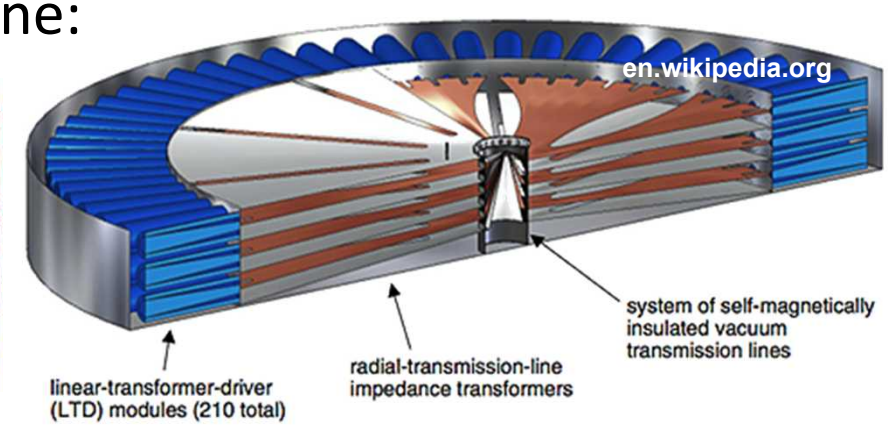
Build AFRL's SHIVA Star

Or SNL's Saturn

Or Various Iterations of SNL Z Machine:





Summary

- Reviewed Basic Electrical Components for Pulsed Power
- Reviewed Transmission Lines for Pulsed Power
- Learned About Marx banks and How to Trigger Them
- Things we didn't mention: Inductive Energy Stores, Blumleins, Solid State Triggering, Metamaterials…

To Learn More…

- There are lots of good books on the subject:
  - *J.C. Martin on Pulsed Power*, by T.H. Martin, et al, 1996
  - *Pulsed Power*, by G.A. Mesyats, 2005
  - *Transient Electronics*, by P.W. Smith, 2002
  - *High Speed Pulse Technology* (2 vols.), by F. Frungel, 1965
  - *Pulse Generators* (MIT Rad Lab Series), by Glasoe and Lebacqz, 1948
  - *Electronic Gadgets for the Evil Genius*, by B. Iannini, 2004
- Try the Power Modulator/High Voltage conference this summer (San Francisco, CA): http://www.ipmhvc.com/2016/
- Also Texas Tech has their annual short course: http://www.p3e.ttu.edu/shortcourse2015/
- The Pulsed Power Formulary is available for free online: http://www.highvoltageprobes.com/_literature_89707/Pulsed_Power_Formulary
- As is material from the US Particle Accelerator School (e.g.): http://uspas.fnal.gov/materials/09VU/VU_PulsedPowerEng.shtml
- Finally, this guy builds smaller pulsed power stuff: http://www.electricstuff.co.uk/marxgen.htm

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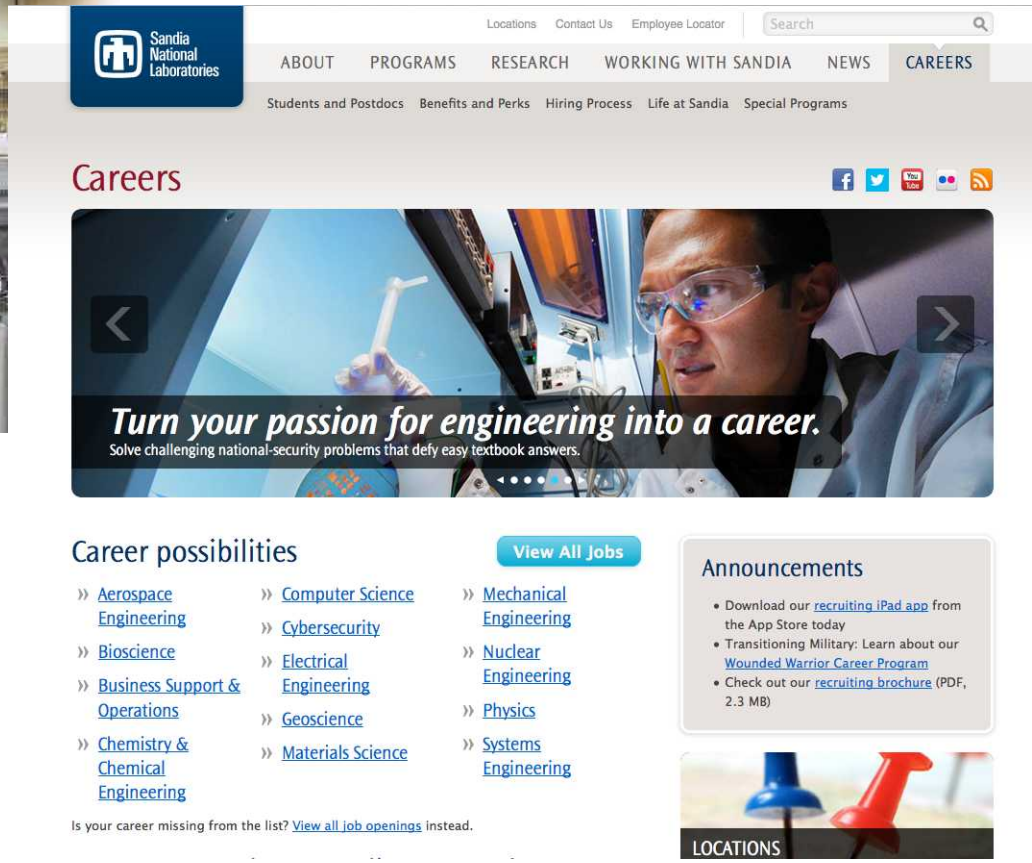
sandia.gov/careers



Questions?


I have no idea what you're talking about...
forums.archeagegame.com
...so here's a bunny with a pancake on its head.