Overview: Monte Carlo Radiative Energy Deposition (MRED) Code

What does MRED compute?

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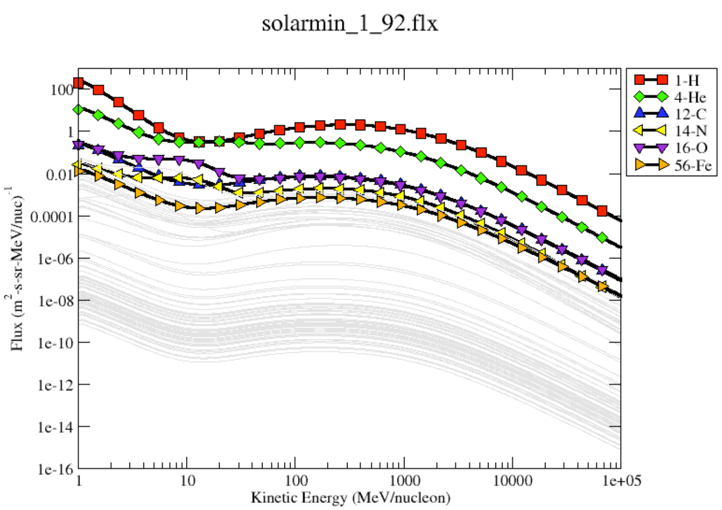
Outline

- SEU rate prediction
  - The general Monte Carlo method
  - RPP method
  - Collected charge methods
- Criteria for using a Monte Carlo approach
- Status of the CREME96 Revision
- Conclusion

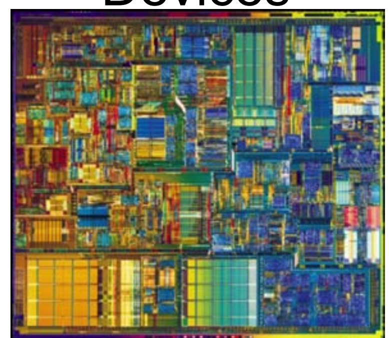
Detailed physical simulation

Do it once; do it right. Leverage supercomputer scaling.

Radiation Environments

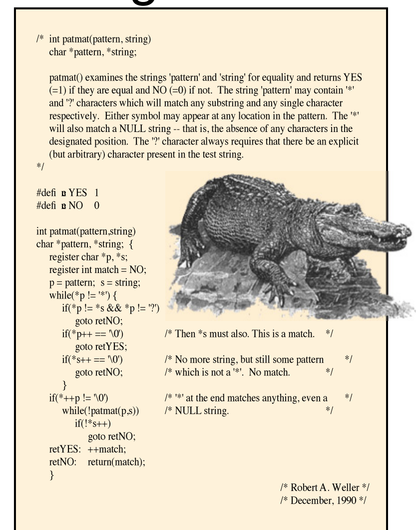


Devices



http://www.icknowledge.com/trends/p4(2).jpg

Algorithms

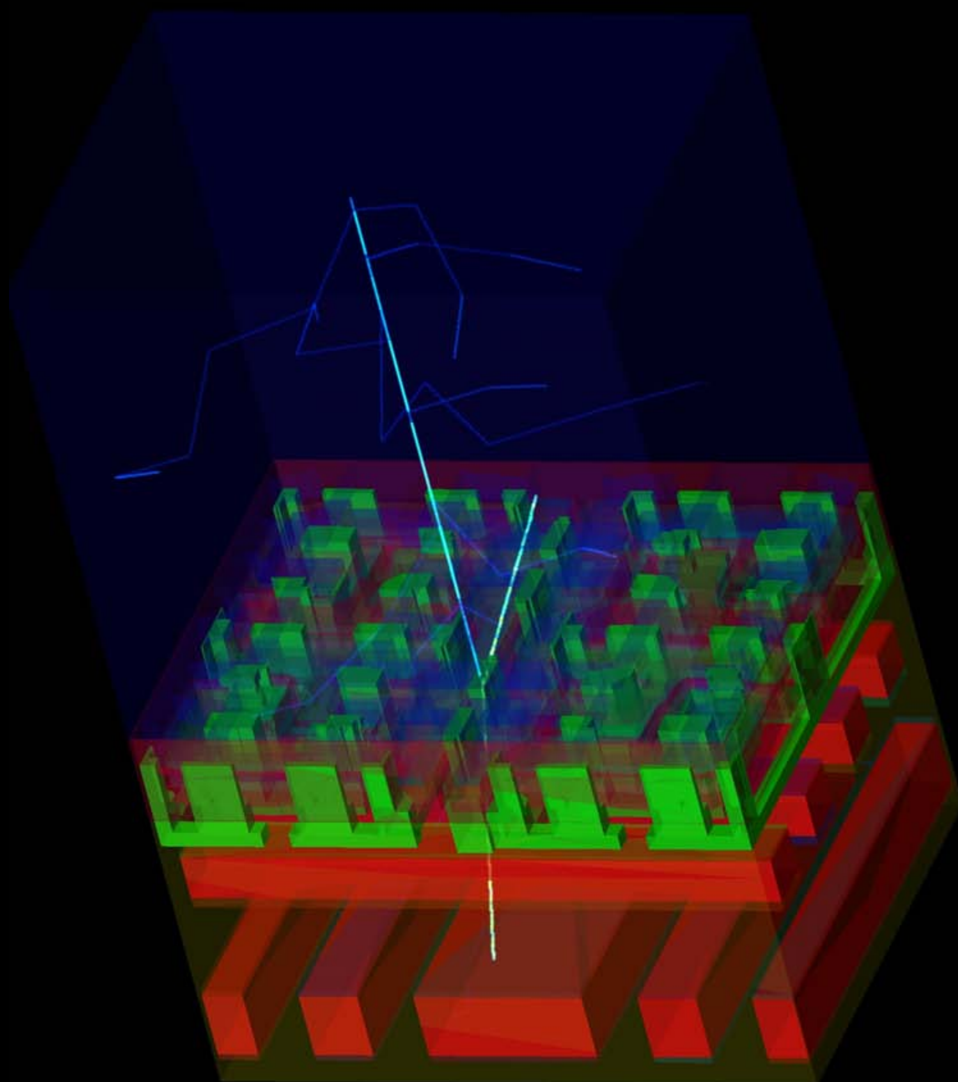


```
/*  int patmat(pattern, string)
    char *pattern, *string;

    patmat() examines the strings 'pattern' and 'string' for equality and returns YES
    (=1) if they are equal and NO (=0) if not.  The string 'pattern' may contain '*'
    and '?' characters which will match any substring and any single character
    respectively.  Either symbol may appear at any location in the pattern.  The '*'
    will also match a NULL string -- that is, the absence of any characters in the
    designated position.  The '?' character always requires that there be an explicit
    (but arbitrary) character present in the test string.
*/

#define YES   1
#define NO    0

int patmat(pattern,string)
char *pattern, *string;  {
    register char *p, *s;
    register int match = NO;
    p = pattern;  s = string;
    while(*p != '*') {
        if(*p != *s && *p != '?')
            goto retNO;
        if(*p++ == '\0')            /* Then *s must also. This is a match.    */
            goto retYES;
        if(*s++ == '\0')            /* No more string, but still some pattern    */
            goto retNO;             /* which is not a '*'.  No match.            */
        }
    if(*++p != '\0')                /* '*' at the end matches anything, even a   */
        while(!patmat(p,s))         /* NULL string.                              */
            if(!*s++)
                goto retNO;
    retYES:  ++match;
    retNO:   return(match);
    }
                                    /* Robert A. Weller */
                                    /* December, 1990 */
```

Croc image: http://crocodilian.com/crocfaq/

Supercomputer

A simulated radiation event



Monte Carlo simulation

- **MRED**: A Monte Carlo engine to determine a probability distribution by repetitive sampling.
- **Monte Carlo**: Appropriate when analytical computations are impractical.
- **Example**: "The probability density for an isotropic, mono-energetic flux of ions with atomic number z and energy E_0 to deposit energy E in a specific volume?"

http://ecx.images-amazon.com/images/I/411nB42M-7L._AA260_.jpg

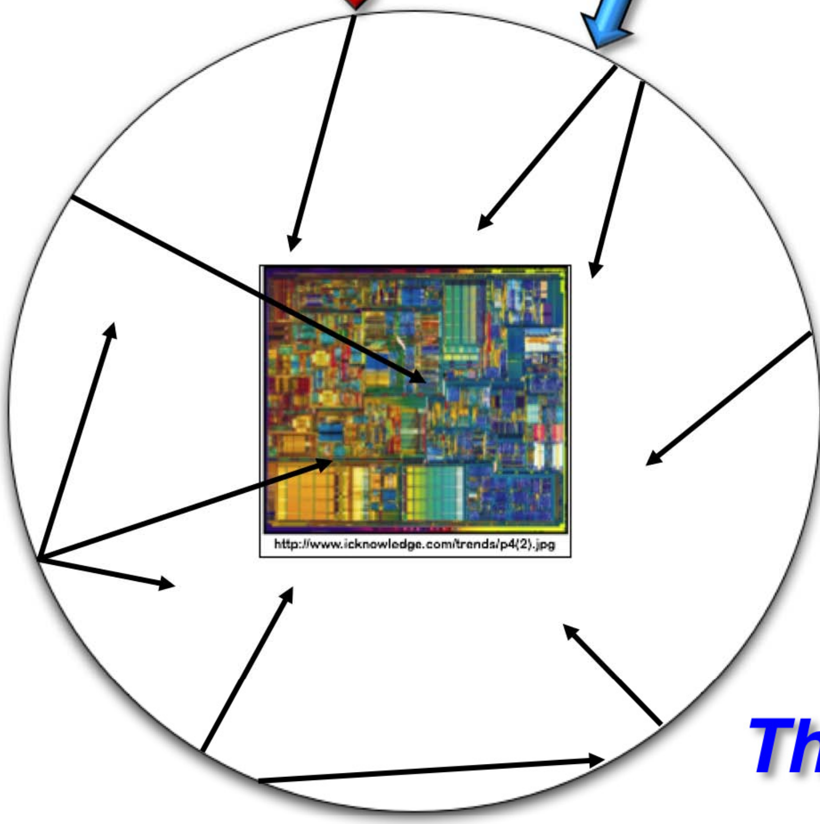
SEE rate: What MRED computes

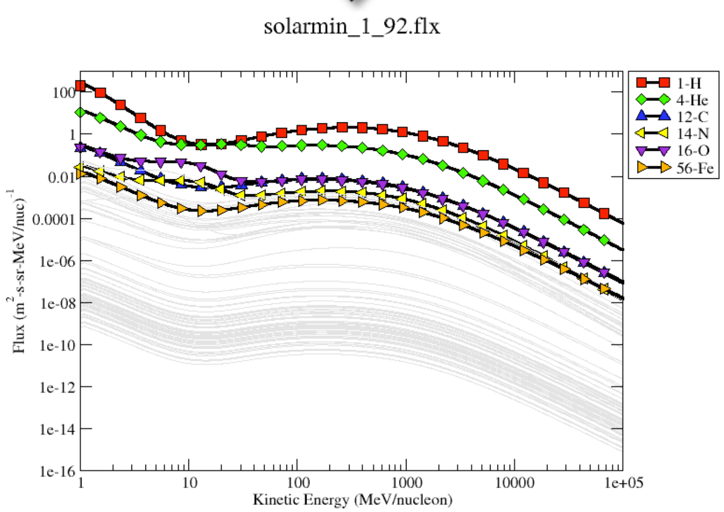
Effect rate

Probability of an effect

$$R(t) = -\sum_{z} \int_{All\,E} dE \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e} \int_{-\infty}^{t} dt' \; \Phi(z,E,\hat{e},\vec{x},t') \times P_e(z,E,\hat{e},\vec{x},t';t)$$

$(z,E,\hat{e},\vec{x},t')$





The world

The common simplifying assumptions

$$R(t) = -\sum_z \int_{All\,E} dE \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e} \int_{-\infty}^{t} dt' \;\Phi(z,E,\hat{e},\vec{x},t') \times P_e(z,E,\hat{e},\vec{x},t';t)$$

The event and effect are instantaneous…

$$P_e(z,E,\hat{e},\vec{x},t';t) \equiv \lim_{\varepsilon\to 0} P_e(z,E,\hat{e},\vec{x}) \cdot \delta(t' - (t-\varepsilon))$$

The flux is time independent…

$$\Phi(z,E,\hat{e},\vec{x},t) \equiv \Phi(z,E,\hat{e},\vec{x})$$

The flux is isotropic and homogeneous…

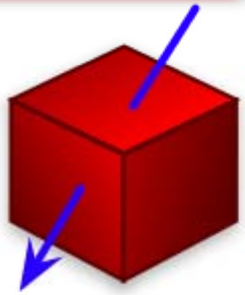
$$\Phi(z,E,\hat{e},\vec{x}) \equiv \Phi(z,E)$$

$$R = -\sum_z \int_{All\,E} dE \;\Phi(z,E) \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e} \;P_e(z,E,\hat{e},\vec{x})$$

RPP model assumptions

$$R = -\sum_{z} \int_{All\ E} dE\ \Phi(z,E) \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e}\ P_e(z,E,\hat{e},\vec{x})$$

The world is a rectangular parallelepiped…



The event probability is completely determined by the energy deposited in the world…

$$P_e(z,E,\hat{e},\vec{x}) \equiv \int p_d(z,E,\hat{e},\vec{x},E_d)\ P_e(E_d)\,dE_d$$

Deposited energy is completely determined by LET, which is constant…

$$p_d(z,E,\hat{e},\vec{x},E_d) = \delta(E_d - h(\hat{e},\vec{x})S(z,E))$$

The event occurs if and only if the deposited energy exceeds a critical threshold…

$$P_e(E_d) = H(E_d - E_c)$$ ***= Unit step function***

The chord-length distribution emerges

$$\lambda = \frac{E_d}{S(z,E)}$$

$$R(E_c) = \pi A \sum_z \left(\int dE\, \Phi(z,E) \int_{\frac{E_c}{S(z,E)}}^{\infty} d\lambda \left(\frac{-1}{\pi A} \int_{\hat{n}(\vec{x})\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e}\; \delta(\lambda - h(\hat{e},\vec{x})) \right) \right)$$

Differential path length distribution

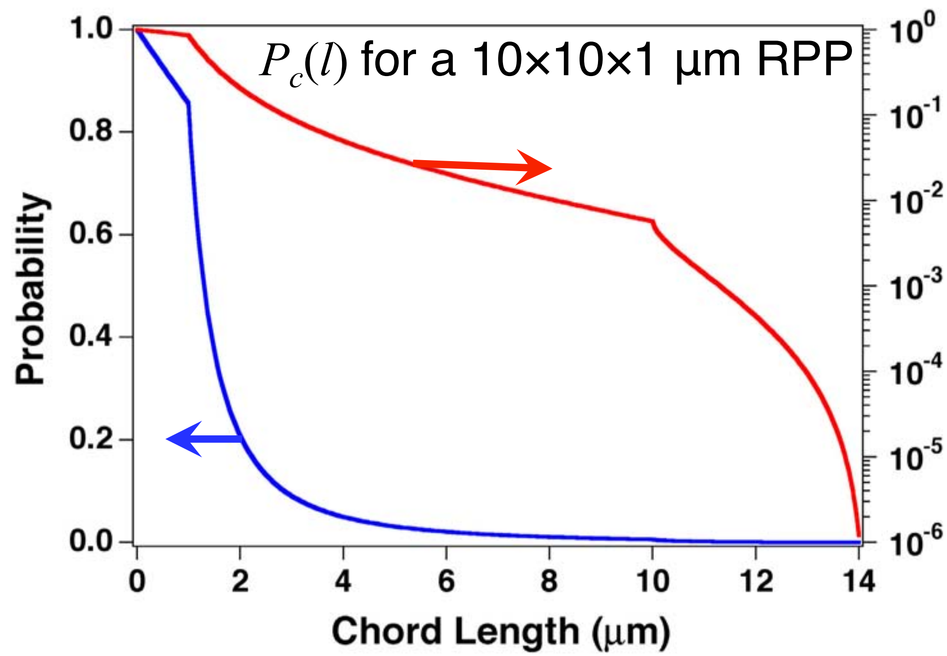
$$p_c(l) \equiv \frac{-H(l)\,H(l_{\max} - l)}{\pi A} \int_{\hat{n}(\vec{x})\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e}\; \delta(l - h(\hat{e},\vec{x}))$$

Integral path length distribution

$$P_c(l) \equiv \int_l^{\infty} p_c(x)\,dx$$

The RPP Rate

$$R(E_c) = \pi A \sum_z \left(\int dE\, \Phi(z,E)\, P_c\!\left(\frac{E_c}{S(z,E)}\right) \right)$$



The LET distribution emerges

Dirac delta

$$R(E_c) = \pi A \int ds \left(\sum_z \left(\int dE\, \Phi(z,E)\, \delta\left(s - S(z,E)\right) \right) \right) \cdot P_c\left(E_c / s\right)$$

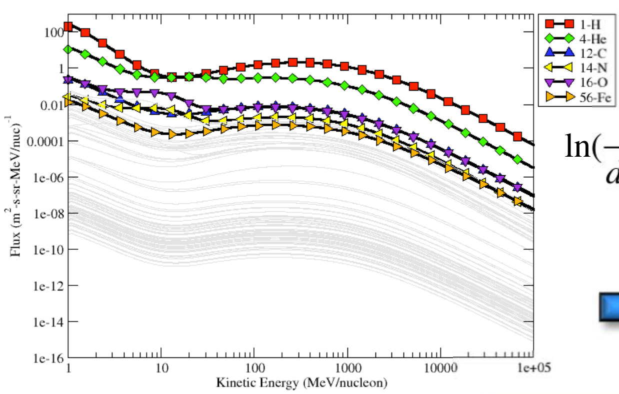
Differential:

$$f(s) = f(s)\,H(s_{\max} - s) \equiv \sum_z \left(\int dE\, \Phi(z,E)\, \delta\left(s - S(z,E)\right) \right) = \sum_z \sum_i \frac{\Phi(z,E_i)}{\left| \left(\frac{dS(z,E)}{dE} \right)_{E=E_i} \right|}$$

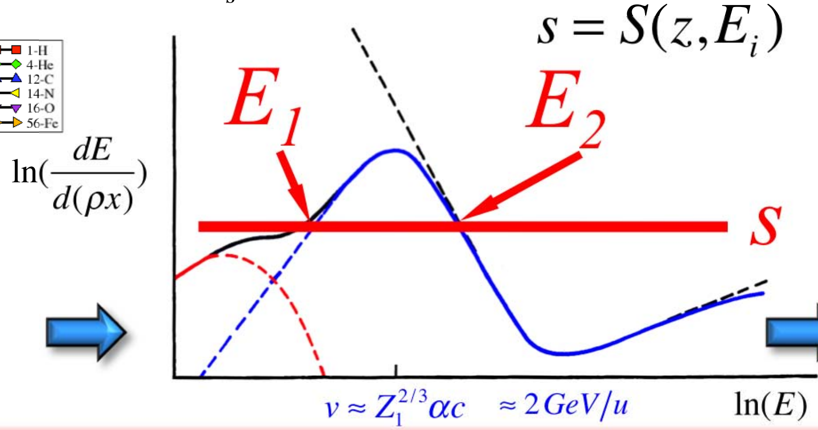
Integral:

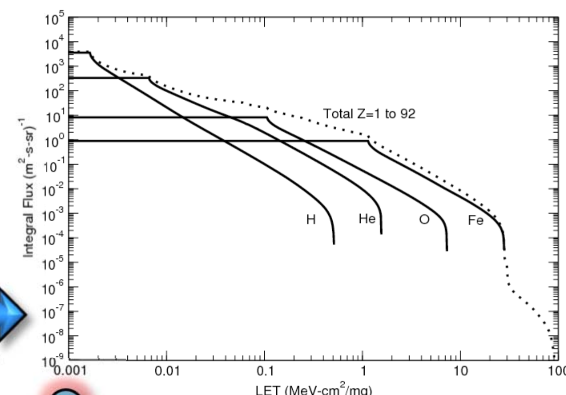
$$F(s) \equiv \int_s^{\infty} f(s')\,ds' = \int_s^{s_{\max}} f(s')\,ds'$$

solarmin_1_92.flx



$$s = S(z,E_i)$$

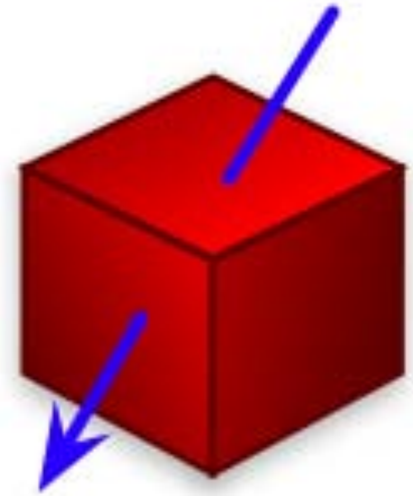




$$R(E_c) = \pi A \int_{E_c/l_{\max}}^{s_{\max}} ds\; f(s)\, P_c\left(\frac{E_c}{s}\right)$$

The RPP model for rate prediction

- Upset follows deposition of critical charge Q_c or equivalent energy, E_c.
- Deposition of $Q > Q_c$ depends on projectile LET and chord-length distribution
- Rate depends on LET distribution in the space environment
- Factors entering into the model
  - Target (RPP) size
  - LET distribution
  - RPP's path length distribution
  - Critical charge for upset
- The upset rate, *R*:



$$R(E_c) = \pi A E_c \cdot \int_{s_{\max}}^{s_{\min}} F(s) p_l(E_c/s) \frac{ds}{s^2}$$

$A = \text{Surface area}$

$l_{\max} = \text{Longest chord}$

$E_c = \text{Energy equivalent of } Q_c$

$s_{\min} = E_c / l_{\max} = \text{Minimum LET for upset}$

$s_{\max} = \text{Maximum environmental LET}$

$F(s) = \text{Integral LET distribution}$

$p_c(x) = \text{Differential path length distribution}$

Effect criterion: Collected charge

$$R = -\sum_{z} \int_{All\,E} dE\ \Phi(z,E) \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e}\ P_e(z,E,\hat{e},\vec{x})$$

Effect probability is determined by collected charge…

$$P_e(z,E,\hat{e},\vec{x}) \equiv \int dQ\ \ p_Q(z,E,\hat{e},\vec{x},Q)P_e(Q)$$

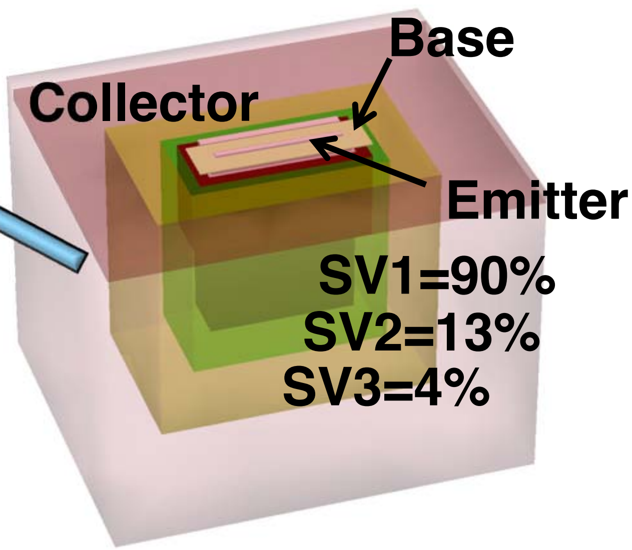
Dirac delta

$$p_Q(z,E,\hat{e},\vec{x},Q) = \int dE_1 \int dE_2 \ldots \int dE_n \delta(Q - \sum_{i=1}^{n} k_i E_i)\, p_{d1}(z,E,\hat{e},\vec{x},E_1)\, p_{d2}(z,E,\hat{e},\vec{x},E_2) \ldots p_{dn}(z,E,\hat{e},\vec{x},E_n)$$

Probability to collect charge Q

Probability for an effect, e.g.: $P_e(Q) \equiv H(Q - Q_c)$

How to evaluate this? MRED!



Multiple Sensitive Volumes

SPICE in the loop – What it really does.

$$R = -\sum_{z} \int_{All\,E} dE\ \Phi(z,E) \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\hat{e}\ P_e(z,E,\hat{e},\vec{x})$$

Recall the single-transistor probability to collect charge Q:

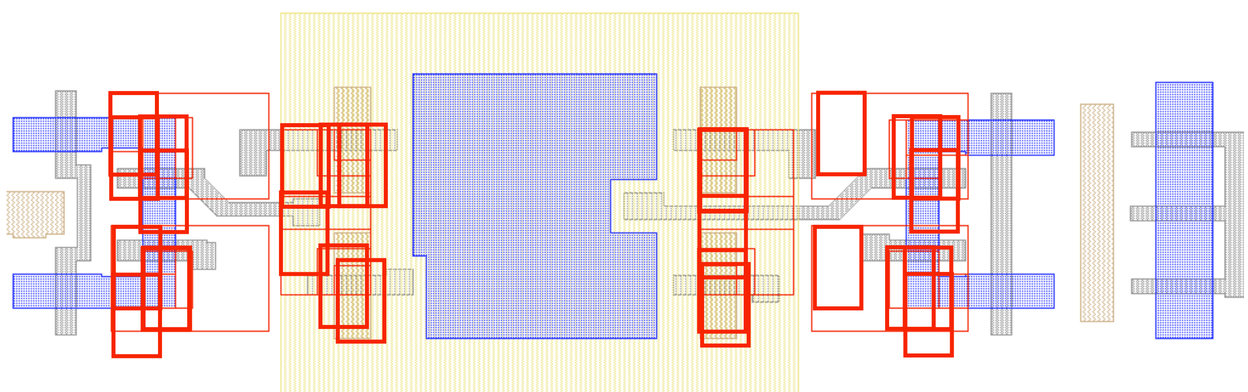
$$p_Q(z,E,\hat{e},\vec{x},Q) = \int dE_1 \int dE_2 \ldots \int dE_n \delta(Q - \sum_{i=1}^{n} k_i E_i)\, p_{d1}(z,E,\hat{e},\vec{x},E_1) p_{d2}(z,E,\hat{e},\vec{x},E_2) \ldots p_{dn}(z,E,\hat{e},\vec{x},E_n)$$

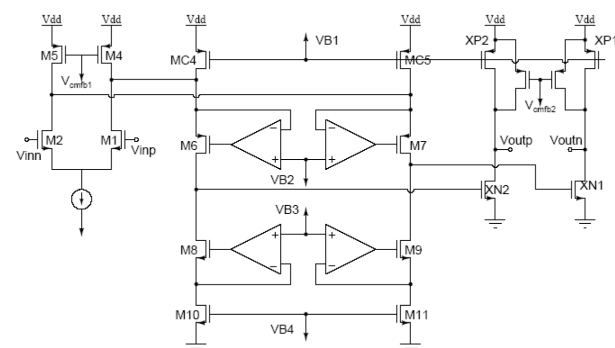
$$P_e(z,E,\hat{e},\vec{x}) \equiv \int dQ_1 \int dQ_2 \ldots \int dQ_n\ p_{Q1}(z,E,\hat{e},\vec{x},Q_1) p_{Q2}(z,E,\hat{e},\vec{x},Q_1) \ldots p_{Qn}(z,E,\hat{e},\vec{x},Q_1) P_e(Q_1,Q_2,\ldots,Q_n)$$

If the effect involves several transistors and a joint probability…

SPICE

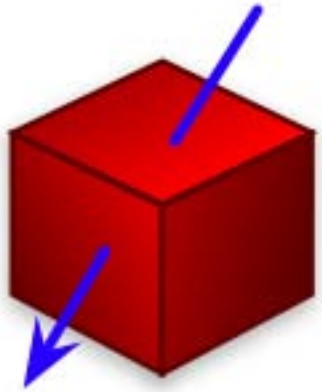
NMOS PMOS NMOS



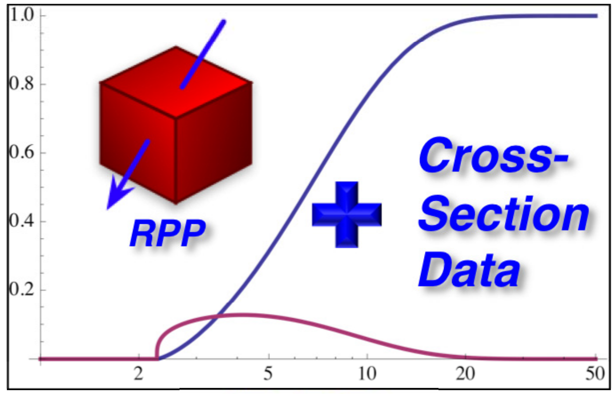


This is the time-independent case…

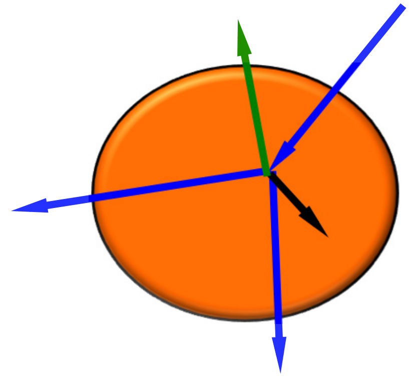
Summary of the approximation hierarchy



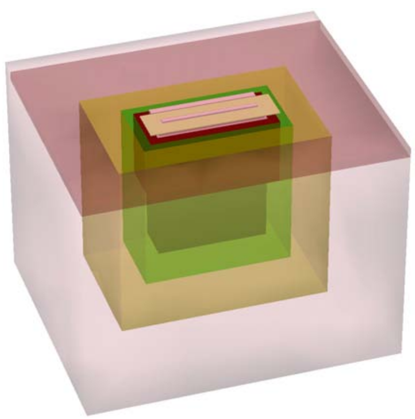
RPP



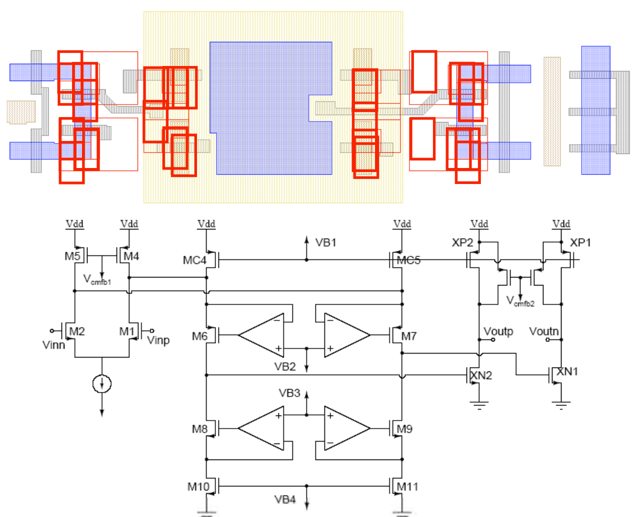
IRPP



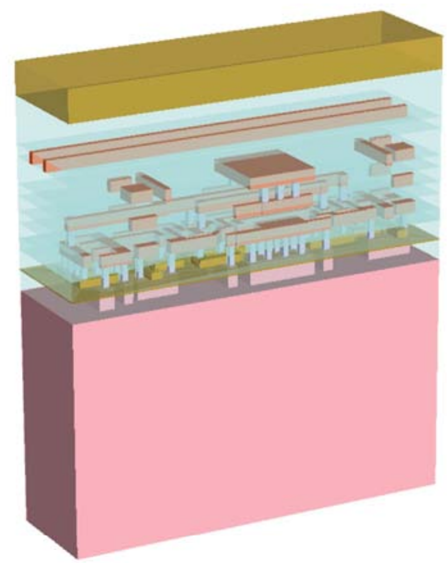
MC: One SV



MC: Nested SVs



MC: SVs +SPICE

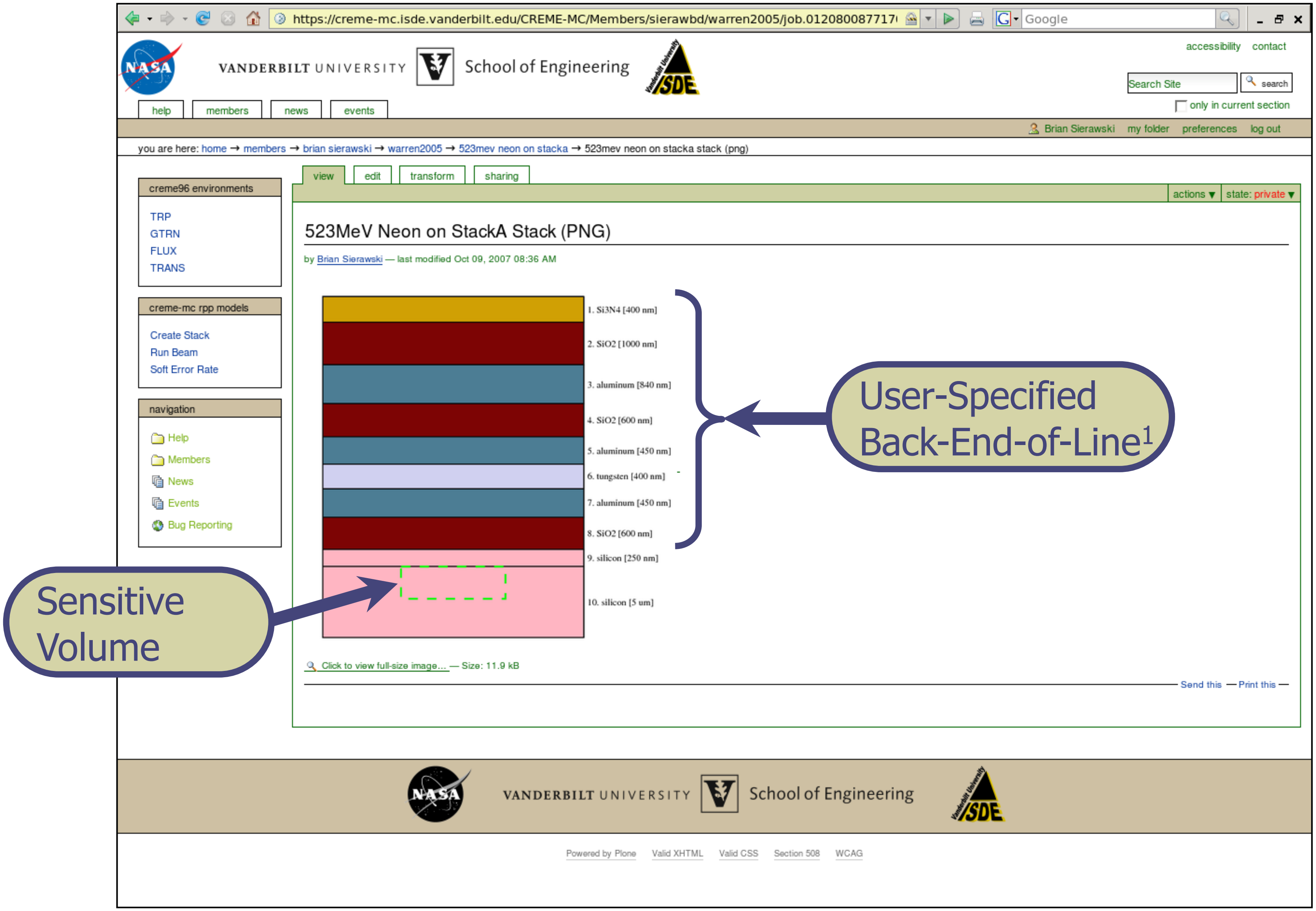


MC: SVs +TCAD

Indicators for Monte Carlo analysis

- **Known technology or system application characteristics:**
  - Basic assumptions of the RPP or IRPP model are known to be inappropriate to the technology under investigation.
  - Upsets are known to require near simultaneous, multiple-transistor, multiple-node perturbations.
- **Experimental observations:**
  - Unexpected upsets are observed in what is assumed to be a hardened technology.
  - Different ions with the same LET produce upset cross-sections that differ statistically.
  - Cross sections for multiple ions cannot be correlated with a single sensitive volume.
  - strong azimuthal angle dependence (rotation around the die surface normal) is observed with heavy ions.
  - Strong angular dependence is evident in test data using protons.

CREME-MC - Status



Conclusion

Thank you!