

Administrative Stuff

- Make sure you sign the sheet
- Credit: minicourse credit (Astro), modular course credit (Physics)
- Homework: due noon following Thursday :
 - will turn around faster this time
 - tar; include makefile, version control log
- Office Hours: Mon, Wed, 3-4pm, McCaul 256 2nd floor
- Info: https://wiki.scinethpc.ca/wiki/index.php/Numerical_Tools_for_Physical_Scientists_%28course%29
- email: {rzon,ljdursi}@scinet.utoronto.ca

Numerical Tools for Physical Scientists

Ramses Van Zon, Jonathan Dursi
SciNet, Jan/Feb 2012

The Course

- We've covered some basics of programming for scientists in the last class:
 - C/C++
 - git for version control
 - unit tests
- Here we're going to focus on specifics of numerical computing for physical scientists.

Course Outline

- Today: Numerics, Random Numbers
- Jan 20: Integration, ODE solvers
- Jan 27: Numerical Linear Algebra - BLAS, LAPACK
- Feb 3: Fast Fourier Transforms - FFTW

Today

- What numerical computing is, and how to think about it
- Modelling vs reality; Validation & Verification
- Real arithmetic on computers - floating point math
- Random Number Generators

Computational Science

- “Third Leg” of Science?
- Different than theoretical science or experimental science; requires skills of each
- “Experimental theory” - exploring complex regions of theory
- Requires note-taking, methodical approach of experimentalists; mathematical chops of theorists; and other knowledge too.

Computational Science

- Often done incredibly badly
- If experimentalists work was of quality of much computational work, we still would be arguing over the charge on an electron
- Experimentalists, theoreticians have had centuries to determine best practices for their disciplines
- Computationalists starting to develop ours - eg this course.

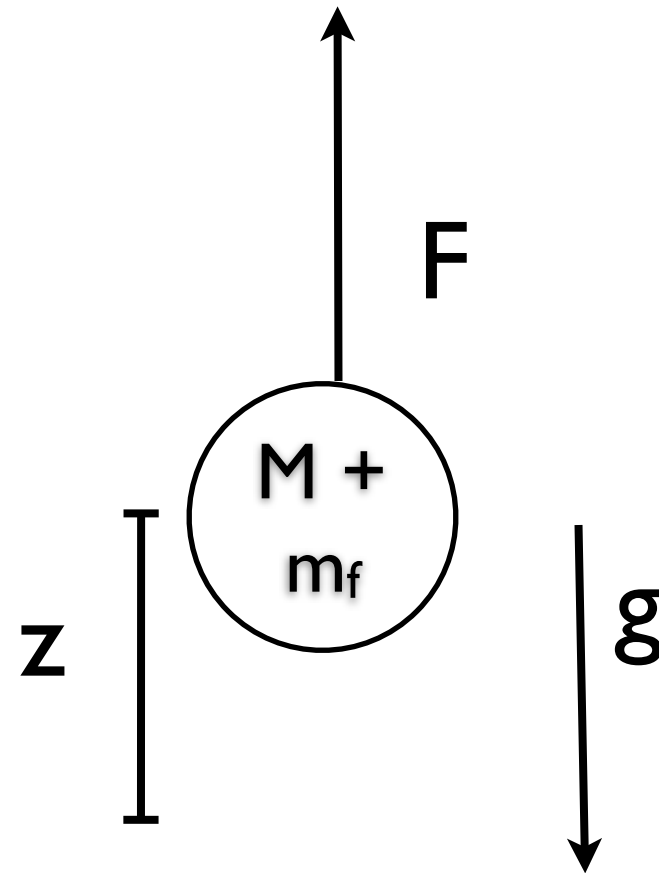
Computational Science

- Computational science, like experimental or theoretical science, is a *modelling* endeavor
- Creating simplified picture of reality that includes (only) bits you want to study.

Phenomenon



Conceptual/ Mathematical Model



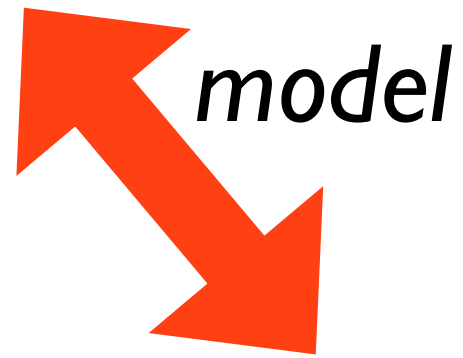
$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

Numerical Computation

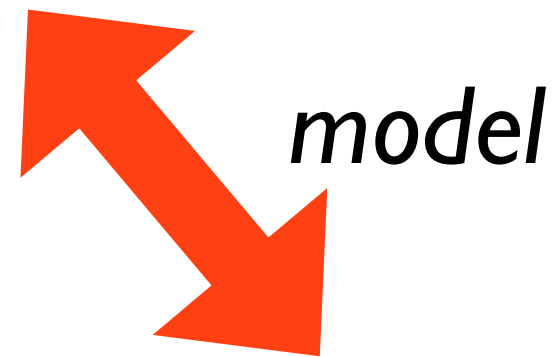
```
double dfdt(double time, double mass, double fuelmass,
            double vel, double force, double z, double dt,
            double *df) {
    double g = Mearth*newtonG/(z*z);
    df[0] = (mass+fuelmass)*(alpha*burnrate-g);
    df[1] = vel;
    df[2] = burnrate;
}
```

1,1 All

Phenomenon



Conceptual/
Mathematical Model



Numerical
Computation

Can go wrong at each step

Are we solving the right equations?



$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

```
double dFdt(double time, double mass, double fuelmass,
             double vel, double force, double z, double dt,
             double *dF) {
    double g = MarchNewtonG(z*x);
    dF[0] = (mass+fuelmass)*(alpha*burnrate-g);
    dF[1] = vel;
    dF[2] = burnrate;
}
```

Can go wrong at each step



$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

Are we solving the equations right?

```
double dFdt(double time, double mass, double fuelmass,
double vel, double force, double z, double dt,
double *dF) {
    double g = MarchNewtonG(z*x);
    dF[0] = (mass+fuelmass)*(alpha*burnrate-g);
    dF[1] = vel;
    dF[2] = burnrate;
}
```

Verification: Testing math \Rightarrow numerics

- Can go wrong in translation from mathematical model to computational model
- Discretization error, Truncation error, roundoff, ... or just plain bug.
- Process of testing this: Verification

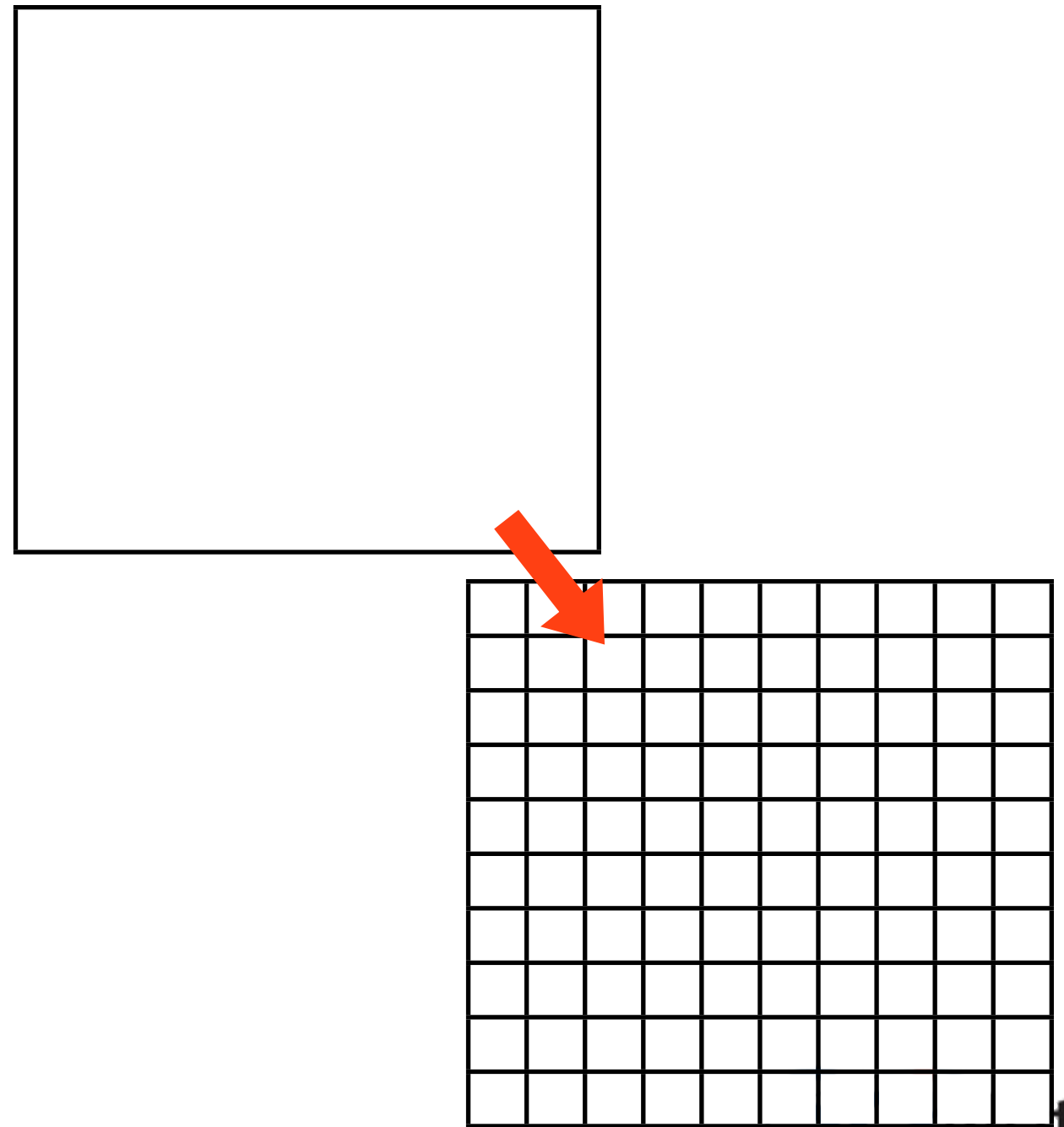


$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

```
double dFdt(double time, double mass, double fuelmass,
             double vel, double force, double z, double dt,
             double *dF) {
    double g = MarchNewtonG(z*time);
    dF[0] = (mass+fuelmass)*(alpha*burnrate-g);
    dF[1] = vel;
    dF[2] = burnrate;
}
```

Discretization error

- Error caused by going from continuum to discrete domain
- Eg: grid in space; discrete timesteps; etc.
- Should decrease as you increase resolution.



Truncation Error

- Typically occurs when an expansion is truncated

$$e^x \approx 1 + x + \frac{x^2}{2}$$

Roundoff

- Floating point mathematics can go wrong (more on this later)

$$(a + b) + c \neq a + (b + c)$$

Just plain bugs

- Scientific software can get large, complex
- Bugs creep in
- Unit testing, version control can greatly help
- Still happens



Verification: Analytics, Bechmarks, Comparisons

- Trying to make sure we are correctly solving the intended equations in the regime of interest.
- Comparison to known analytic solutions:
 - Easy to do
 - Solutions tend to be of very simple situations - not hard tests of the computation, particularly integrated.
 - But very useful for unit tests.

Verification: Analytics, Bechmarks, Convergence

- Trying to make sure we are correctly solving the intended equations in the regime of interest.
- Benchmarking a complex solution from your code to that of another code (could be: same code last year, saved results)
- CAN NOT show that either solution is *correct*
- CAN show that at least one code/version has a problem, or that something has caused changes.

Verification: Analytics, Bechmarks, Convergence

- Trying to make sure we are correctly solving the intended equations in the regime of interest.
- Convergence testing: compare solutions at higher and higher resolution (or terms in expansion, or...)
- Again, doesn't mean converges to correct result, but lack of convergence indicates a problem
- Relatedly - does slightly varying input parameters, result in robust result, or do huge changes occur in relevant metrics?

Validation: Testing reality \Rightarrow numerics

- Can go wrong in translation from phenomenon to mathematical model



$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

```
double dFdt(double time, double mass, double fuelmass,
            double vel, double force, double z, double dt,
            double *dF) {
    double g = MarchNewtonG(z*x);
    dF[0] = (mass+fuelmass)*(alpha*burnrate-g);
    dF[1] = vel;
    dF[2] = burnrate;
}
```

Validation: Testing reality \Rightarrow numerics

- Can go wrong in translation from phenomenon to mathematical model
- Typically only implementation of full mathematical model you have is the code
- Testing code against reality

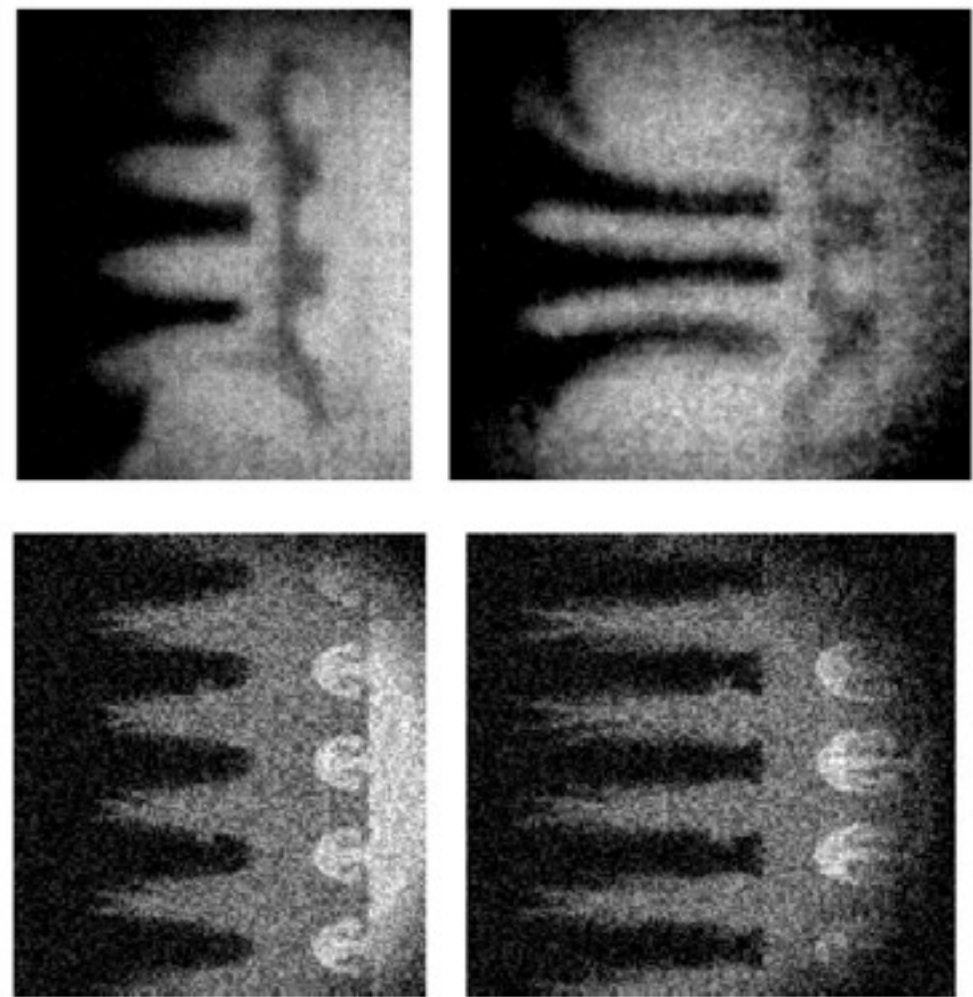


$$\ddot{z} = m(t)(F - g)$$
$$\dot{m}_f \propto F$$

```
double dFdt(double time, double mass, double fuelmass,
             double vel, double force, double z, double dt,
             double *dF) {
    double g = MarchNewtonG(z*x);
    dF[0] = (mass+fuelmass)*(alpha*burnrate-g);
    dF[1] = vel;
    dF[2] = burnrate;
}
```

Validation: Code/ Experiment comparisons

- Only way to do validation is to compare directly to experimental results
- Must be in regime you are realistically interested in, but still experimentally accessible
- Requires collaboration with experimentalists.
- Proves that there's a regime in which your code accurately reproduces reality.

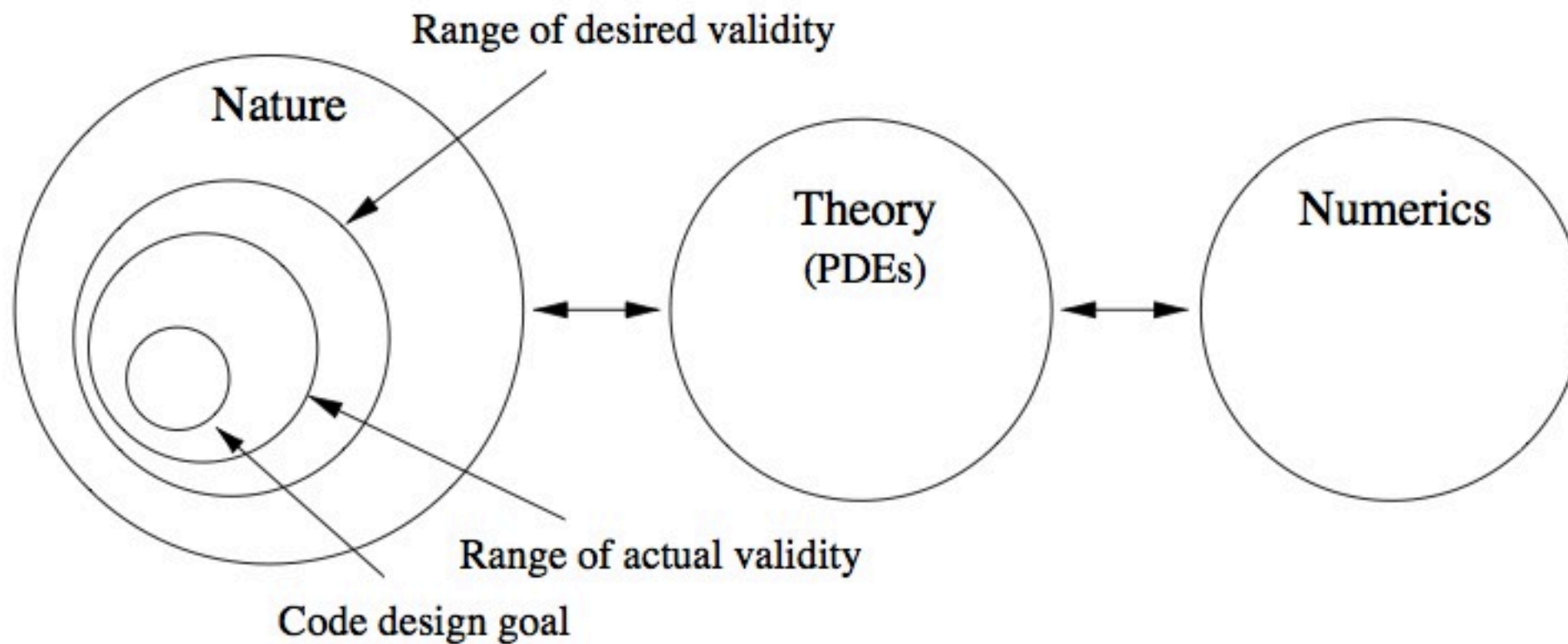


arXiv:astro-ph/0206251

Not a one-off

- Even after an extensive V&V effort, code changes
- Still giving right answer?
- Unit tests, **regular** integrated tests crucial to *maintaining* correctness
- Who cares that your code once gave correct answer *once*, some Thursday two years ago?

Regimes of Interest



Floating Point Mathematics

Like real numbers, but different.

Integer Math and Computers

- Infinite number of integers
- Finite size of integer representation
- Finite range. One bit for sign; can go from -2^{31} to (almost) 2^{31} ($-2,147,483,648$ to $2,147,483,647$)
- Unsigned: $0..2^{32}-1$

int: 32 bits = 4 bytes



Integer Math and Computers

- long long int:
- One bit for sign; can go from -2^{63} to (almost) 2^{63}
(-9,223,372,036,854,775,808 to 9,223,372,036,854,775,807)

long long int: 64 bits =
8 bytes



- Unsigned: $0..2^{64}-1$

Integer Math and Computers

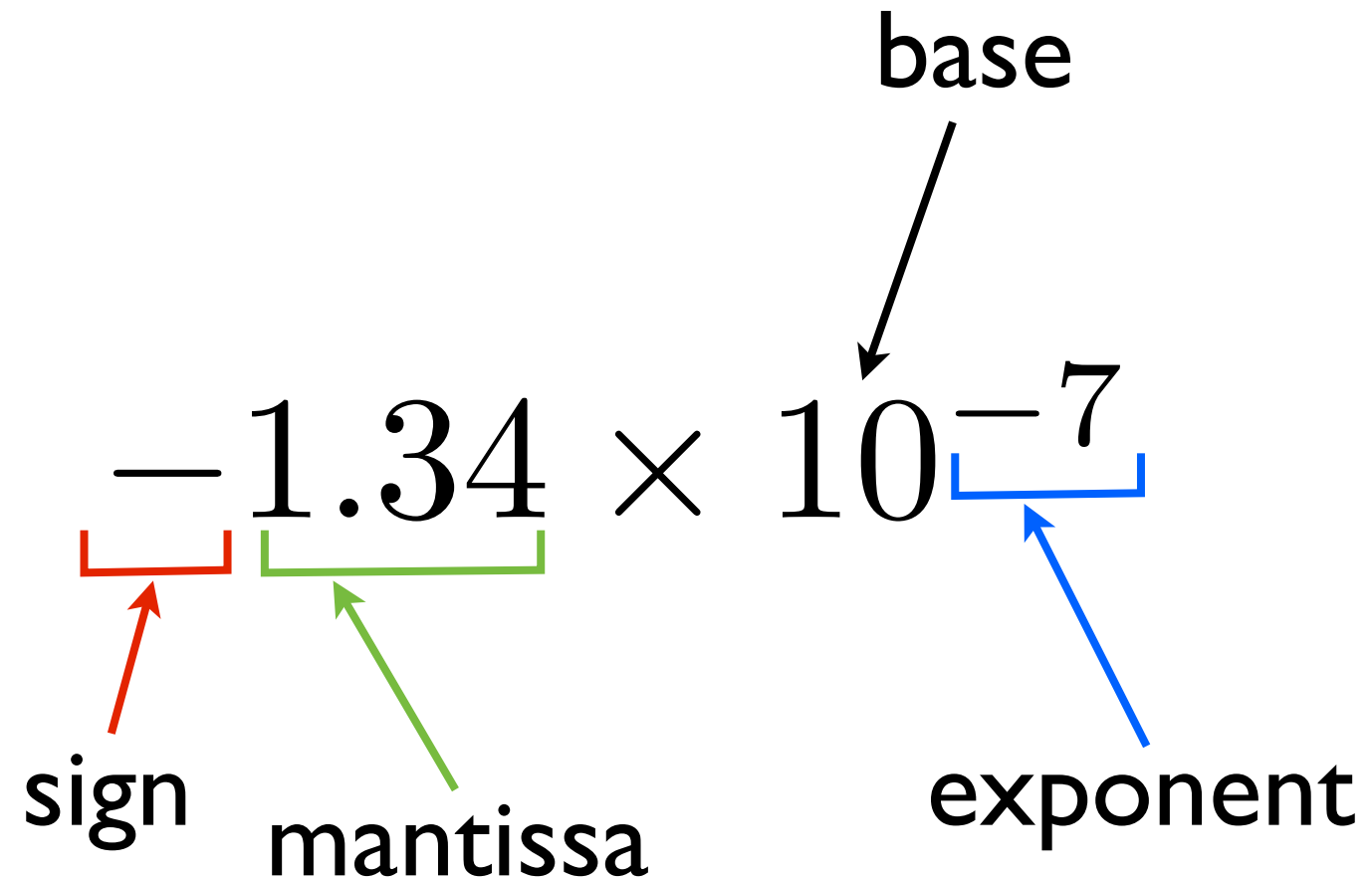
- All integers within range are exactly representable.
- Absolute spacing (1) constant across range; relative spacing varies
- All operations (+,-,*) between representable integers represented unless overflow (with either sign)

Fixed point numbers

- Could treat real numbers like integers - $0 \dots \text{INT_MAX}$, with say the last two digits 'behind decimal point'.
- Financial stuff often uses this; only ever need/want two decimal points
- Horrifically bad for scientific computing - relative precision varies with magnitude; cannot represent small and large numbers at same time.

Floating Point Numbers

- Analog of numbers in scientific notation
- Inclusion of an exponent means point is “floating”
- Again, one bit dedicated to sign



Floating Point Numbers

- **Standard:** IEEE 754
- Single precision real number (float):
- 1 bit sign
- 8 bit exponent (-126..127)
- 23 bit mantissa
- double precision: 1/11/52

$$\underbrace{-}_{\text{sign}} \underbrace{1.34}_{\text{mantissa}} \times \underbrace{10^{-7}}_{\text{exponent}}$$

base



Floating Point Numbers

- To ensure uniqueness of representation (don't waste patterns), first bit of mantissa always 1.
- Since always 1, don't need to store it
- Really 24 (53) bits of mantissa
- Normalized numbers

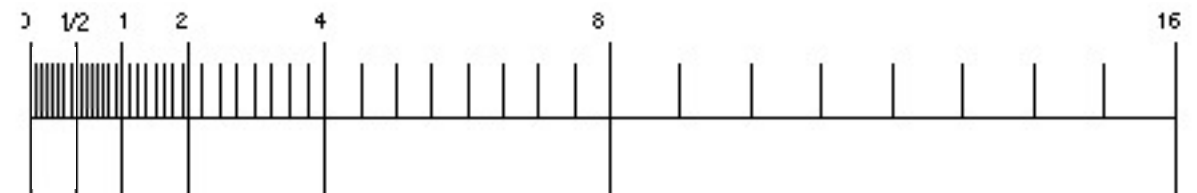
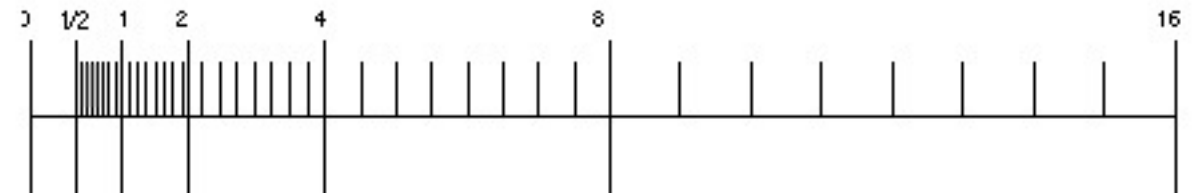
$$\underbrace{-}_{\text{sign}} \underbrace{1.34}_{\text{mantissa}} \times \underbrace{10^{-7}}_{\text{exponent}}$$

base



Denormal numbers

- This actually leads to a big jump between smallest possible number and zero
- Relative accuracy doesn't degrade gracefully
- So *if* exponent = minimum, assume first bit of mantissa = 0



Special “Numbers”

- There’s room in the format for the storing of a few special numbers:
- Signed infinities (+Inf, -Inf): result of overflow, or divide by zero.
- Signed zeros - signed underflow, or divide by +/-Inf
- Not a Number - NaN. Sqrt of a negative, 0/0, Inf/Inf, etc.
- All of the events which lead to these are (usually) errors and can be made to cause exceptions.

Underflow: mostly harmless?

- Try the following:
- Repeatedly take sqrts, then square a number
- Plot this from 0..2
- What should you get? What do you get?
- Like cancellation, loss of precision in early stage of calculation can cause problem

```
In [9]: def sqrts(x):  
...:     y = x  
...:     for i in xrange(128):  
...:         y = sqrt(y)  
...:     for i in xrange(128):  
...:         y = y*y  
...:     return y  
...:
```

```
In [10]: x = linspace(0.,2.,1000)
```

```
In [11]: y = sqrts(x)
```

```
In [12]: plot(x,y,'o-')
```

Floating Point Exceptions

- Let's look at the following Fortran code
- Second division should fail
- If compile and run as is, will just print NaN for C
- Can have it stop at error:

```
program nantest
  real :: a, b, c

  a = 1.
  b = 2.

  c = a/b
  print *, c,a,b

  a = 0.
  b = 0.

  c = a/b
  print *, c,a,b

  a = 2.
  b = 1.

  c = a/b
  print *,c,a,b
end program nantest
```

Floating Point Exceptions

- Compiling with gfortran, can give -ffpe-trap options
- will trap (throw exception, stop) for invalid, divide by zero, overflow
- Could also do underflow
- Debugger stops at line that causes exception

```
$ gfortran -o nantest nantest.f90
      -ffpe-trap=invalid,zero,overflow -g

$ gdb nantest
[...]
(gdb) run
Starting program: /scratch/ljdursi/Testing/fortran/nan
0.50000000      1.00000000      2.00000000

Program received signal SIGFPE, Arithmetic exception.
0x0000000000400384 in nantest () at nantest.f90:13
13              c = a/b
Current language: auto; currently fortran
```

Floating Point Exceptions

- C: include fenv.h, and use feenableexcept (enable exceptions)
- constants defined
- gdb again works

```
#include <stdio.h>
#include <fenv.h>

int main(int argc, char **argv) {
    float a, b, c;
    feenableexcept(FE_DIVBYZERO | FE_INVALID | FE_OVERFLOW);

    a = 1.;
    b = 2.;

    c = a/b;
    printf("%f %f %f\n", a, b, c);

    a = 0.;
    b = 0.;

    c = a/b;
    printf("%f %f %f\n", a, b, c);

    a = 2.;
    b = 1.;

    c = a/b;
    printf("%f %f %f\n", a, b, c);

    return 0;
}
```

Floating Point Exceptions

- C: include `fenv.h`, and use `feenableexcept` (enable exceptions)
- constants defined
- gdb again works

```
$ gcc -o nantest nantest.c -lm -g
$ gdb ./nantest
[...]
(gdb) run
Starting program: /scratch/s/scinet/ljdursi/Testing/exception/nantest
1.000000 2.000000 0.500000

Program received signal SIGFPE, Arithmetic exception.
0x00000000004005d0 in main (argc=1, argv=0x7fffffffef41)
nantest.c:17
17      c = a/b;
```


Floating Point Math

- Fire up Python, and try the following:

```
In [1]: print 1  
1
```

```
In [2]: print 1.e-17  
1e-17
```

```
In [3]: print (1. + 1.e-17) - 1.  
??
```

Floating Point Math

- Fire up Python, and try the following:

```
In [1]: print 1  
1
```

```
In [2]: print 1.e-17  
1e-17
```

```
In [3]: print (1. + 1.e-17) - 1.  
0.0
```

Errors in Floating Point Math

- Assigning a real to a floating point variable involves truncation
- Error of 1/2 ulp (unit in last place) due to rounding due to assignment to finite precision
- (single precision: 1 part in $2^{-24} \sim 6e-8$; double, $1e-16$)

$$\begin{aligned}x &= 1/5 = 0.2_{10} \\ &= 0.001100110011\dots_2 \\ &\ominus 0.0011_2\end{aligned}$$

Rounding

- Rounding should not introduce any systematic biases
- IEEE 754 defines 4 rounding modes:
 - to nearest (even in ties): default
 - to 0 (truncate)
 - to +Inf (round up)
 - to -Inf (round down)

Don't test for equality!

- Because of this error in assignments, and other small perturbations we'll see, testing for floating point equality is prone to failure.
- Generally don't test for $x == 0$, or $x == y$
- $\text{abs}(x) < \text{tolerance}$, or $\text{abs}(x-y) < \text{tolerance}$

Rounding

- Can set rounding mode
 - C: `#include <fenv.h>, fesetround()`
 - `FE_TONEAREST, FE_UPWARD, FE_DOWNWARD, FE_TOZERO`
- Fortran: `use, intrinsic IEEE_ARITHMETIC`
 - `call IEEE_SET_ROUNDING_MODE(),`
 - `IEEE_DOWN, IEEE_UP, IEEE_TO_ZERO, IEEE_NEAREST`

Machine Epsilon

- Let's work in base 10, with mantisa precision=3 and exponent precision=2.
- (ignore denormal/normalized for now; weird with non-binary)
- $| + 0.001$

Machine Epsilon

- Let's work in base 10, with mantisa precision=3 and exponent precision=2.
- (ignore denormal/normalized for now; weird with non-binary)
- $| + 0.001$
- There are numbers x such that $| + x = |$ even though x isn't 0!

$$1 + 10^{-3}$$

$$\begin{array}{r} 1.00 \times 10^0 \\ + 1.00 \times 10^{-3} \\ \hline \end{array}$$

$$\begin{array}{r} 1.00 \times 10^0 \\ + 0.001 \times 10^{-3} \\ \hline \end{array}$$

$$\oplus 1.00 \times 10^0$$

Machine Epsilon

- Defined to be the smallest number s.t. $1+x \neq 1$
- (or sometimes, the largest number s.t. $1+x = 1$)
- single IEEE precision: $\sim 1.19209e-07$; double, $\sim 2.22045e-16$
- By repeated halving, try to see if you can calculate machine epsilon this way. What precision is default floating point number in python?

Machine Epsilon

```
In [4]: x = 1.
```

```
In [5]: while 1. + x > 1.:  
       ...:     print x, 1.+x  
       ...:     x = x / 2.
```

```
[...]  
2.22044604925e-16 1.0
```

First lesson of floating point numbers

- Be wary of adding numbers that are potentially of very different magnitude
- Relative size \sim machine epsilon, regardless of absolute magnitude (eg, $10 + 10e_{\text{mach}} \sim 10$).
- What should we do when adding large series of numbers, even if of roughly same magnitude?

Subtraction: cancellation

- The same effect in opposite with subtraction
- Be wary subtracting very **similar** numbers.

$$\begin{array}{r} 1.23 \times 10^0 \\ - 1.22 \times 10^0 \\ \hline \oplus 1.00 \times 10^{-2} \end{array}$$

Subtraction: cancellation

- The same effect in opposite with subtraction
- Be wary subtracting very **similar** numbers.
- “catastrophic cancellation” - lose precision
- Dangerous in intermediate results

$$\begin{array}{r} \begin{array}{l} \text{3 sig fig} \\ \swarrow \end{array} 1.23 \times 10^0 \\ - 1.22 \times 10^0 \\ \hline \oplus 1.00 \times 10^{-2} \\ \begin{array}{l} \swarrow \\ \text{1 sig fig} \end{array} \end{array}$$

$\begin{array}{l} \text{3 sig fig} \\ \swarrow \end{array}$

Things you do know

- Subtraction: if x, y floating-point representable numbers and x within a factor of 2 of y , then FP subtraction exact

$$x/2 < y < 2 \Rightarrow x \ominus y = x - y$$

- Rounding error when adding FP x and y is an FP number, and can be computed:

$$r = x + y - (x \oplus y) \Rightarrow r = b \ominus ((a \oplus b) \ominus a)$$

- subtraction is addition of a negative
- similar results exists for multiplication

Things you **do** know

- Math libraries typically provide functions (sin, cos, sqrt, pow, etc) results accurate to $\sim 1-3$ ulp, for given FP input
- For exact details, check manual

Be cautious, but don't despair

- FP errors are normally not a concern ~ 1 ulp
- Shouldn't normally be biased one way or another - error of N calculations $\sim \sqrt{N}$ ulp
- (Note: iterate trillion computations in single precision - likely have $O(1)$ errors)
- BUT need to be careful, especially of repeatedly iterated calculations or of awkward things early in a long calculation - if (eg) lose much precision early in a multi-stage computation

How do you know if there's a problem?

- Can test:
 - Change precision (single to or from double; fortran allows quad). Does answer significantly change?
 - Perturb calculation at ulp level by changing rounding behaviour. Does answer significantly change?
 - Perturb calculation by slightly changing inputs. Does answer significantly change?
- If you pass 3 tests, some evidence you're doing ok.

Easiest way to avoid problem

- Don't write numerical code when you don't have to!
- If there exist numerical libraries for things you want to do (ODE, integration, FFTs, linear algebra, solvers), *use them*.
- Amongst other benefits, the numerical issues have been worked out in most mature, highly-used code bases.

Things to avoid

- Subtractions of like-sized variables early in calculation
- Sumations of large amounts of numbers, or numbers of widely varying magnitudes
- Testing for exact floating-point equality

Things to do

- Try to keep values normalized in some sense so that all the values you're likely to deal with are of order unity (avoids machine epsilon problems)
- Try to use existing libraries when necessary
- Routinely test your code

Random Number Generation

Introducing uncertainty on purpose

Based on: “Random Numbers in Scientific Computing: An Introduction”,
Katzgraber, arXiv:1005.4117

Need Random Numbers

- For randomly sampling a domain
- Monte Carlo / MCMC simulations
- Stochastic algorithms

Required Properties

- What is a random sequence of numbers?
- Follow some desired distribution
- Unpredictable
- Fast (we may need billions of them)
- Long period (we may need billions of them)
- Uncorrelated

Real Random Numbers

- Can be generated by a physical process, and stored as a list or used in real-time by computer
- Physical process - lava lamp (lavarnd.org), quantum stuff
- Network process - `/dev/urandom`
- Generally slow, expensive, hard/impossible to reproduce for debugging
- Often hard to characterize underlying distribution

Pseudo Random Number Generators

- PRNG
- Software-based; deterministic sequences of numbers based on some starting seed
- “Seem” random, but reproducible (with same seed), often very fast.
- Will assume uniform distribution on $[0, 1)$; given this, can create other distributions

Common Tests: Correlations

$$\varepsilon(N, n) = \frac{1}{N} \sum_{i=1}^N x_i x_{i+n} - E(x)^2$$

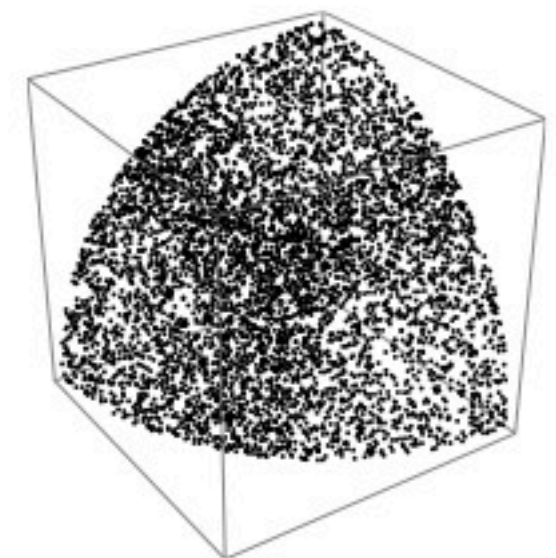
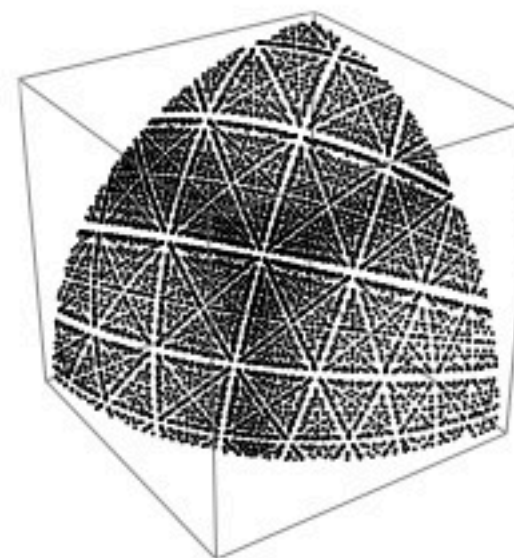
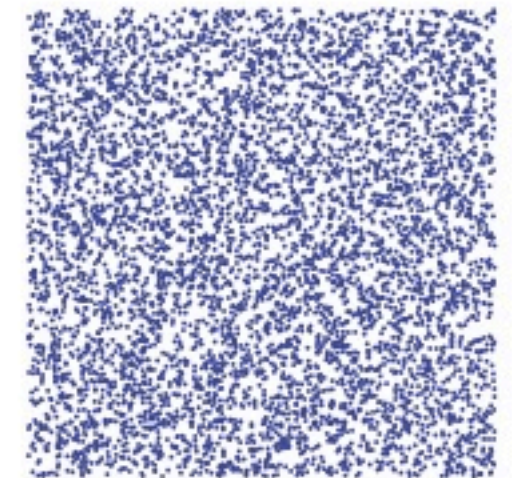
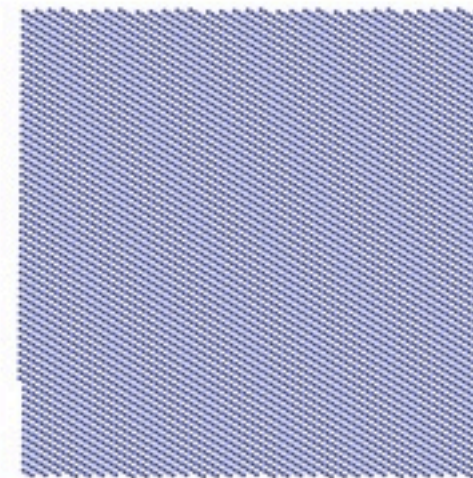
- Simple pairwise correlations:
- Want to avoid correlations between pairs of numbers

$$E(x) = \frac{1}{N} \sum_{i=1}^N x_i$$

$$E(N, n) = O(N^{-1/2}) \quad \forall n$$

Correlations

- What correlations look like in 2d domain
- Left: bad LCG; right: Mersenne Twister



Common Tests: Moments

$$\mu(N, k) = \left| \frac{1}{N} \sum_{i=1}^N x_i^k - \frac{1}{k+1} \right|$$

- Ensure moments of random numbers also have desired properties

$$\mu(N, k) = O(N^{-1/2}) \quad \forall k$$

Other Tests

- Overlapping permutations: Analyze orders of five consecutive random numbers. The $5!$ possible permutations should occur with equal probability
- Parking lot test: pairs of random numbers placed in 2-d domain, exclude others within certain distance. After N attempts, points should follow well known distribution
- Spacings: spacings between random points should follow poisson integral if uniformly distributed
- Binary rank test - test ranks of 32×32 binary matrix

Test suites

- NIST test suite:
<http://csrc.nist.gov/groups/ST/toolkit/rng/index.html>
Very well documented, explain tests.
- Pierre L'Ecuyer, U de Montréal:
<http://www.iro.umontreal.ca/~simardr/testu01/tu01.html>
Test suite in C, includes several PRNGs
- Best test: one that is related to the properties you need for your problem.

Linear Congruential Generators

- x_0 is a seed
- m - large integer;
determines period of
sequence
- For $U(0, 1)$, divide x_i by m .
- For good results: c relatively
prime to m , $a-1$ a multiple of
 p for every prime divisor p
of m , $a-1$ is multiple of 4 if m
is multiple of 4.

$$x_{i+1} = (ax_i + c) \pmod{m}$$

Linear Congruential Generators

- Common, but not very good
- Period limited by size of integers; not enough for some applications.
- Hard to do well in parallel
- **Easy** to mess up, with long history of bad LCGs in standard implementations, literature.

$$x_{i+1} = (ax_i + c) \pmod{m}$$

Linear Feedback Shift Register Generators

- Generalization of LCG
- Good period iff characteristic polynomial defined by a_i is primitive modulo p
- Requires big seed (n x_i s); typically use small seed + good small PRNG to seed
- Still not great - better period (p^n).
- Mersene Twister is a (good) generalization of this.

$$x_i = (a_1 x_{i-1} + \cdots + a_n x_{i-n}) \pmod{p}$$

Lagged Fibonacci

- Some binary operator between previous items in sequence
- Requires some memory
- Requires large seed block again
- m typically large power of 2

$$x_i = (x_{i-j} \odot x_{i-k}) \bmod m$$

Lagged Fibonacci

$$x_i = (x_{i-j} \odot x_{i-k}) \pmod{m}$$

- r1279: k=1279. Period is 10^{394} ; passes tests, and can be fast
- Standard in (eg) GSL

Lagged Fibonacci

- r250: $k = 250$, using xor.
- Also fast, passed all common tests at time
- In 1992, Ferreberg et al did MC simulation of Ising model
- Estimate of energy/per spin was 42σ off!
- PRNGs are hard; **don't** implement yourself.

$$x_i = (x_{i-j} \odot x_{i-k}) \bmod m$$

Some good PRNGs

- r1279
- Mersenne twister (mt19937)
- WELL generators

Not-good PRNGs

- r250
- Anything from Numerical Recipes - short periods, slow, ran0 & ran1 spectacularly fail statistical tests.
- Standard Unix generators (rand(), drand48()) - not a disaster, but short period, correlations.

Non-Uniform Distributions

- Transformation law of probabilities
- Starting with a known distribution (eg, uniform, $p(u) = 1$ in $0..1$), can transform to another distribution ($q(y)$) if can invert function

$$|q(y)dy| = |p(u)du|$$
$$\Rightarrow q(y) = p(u) \left| \frac{du}{dy} \right|$$

Exponential Dist.

- Example: exponential distribution
- Easy to invert, differentiate
- Can get exponential distribution by taking \ln of uniform random numbers.

$$|q(y)dy| = |p(u)du|$$
$$\Rightarrow q(y) = p(u) \left| \frac{du}{dy} \right|$$

$$q(y) = a \exp(-ay)$$

$$\left| \frac{du}{dy} \right| = a \exp(-ay)$$

$$u(y) = \exp(-ay)$$

$$y = -\frac{1}{a} \ln(u)$$

Box-Muller: Gaussian Random Numbers

- Same process can be applied to more complex dists, with some tricks.
- For gaussian, can't do it in 1d, but can in 2
- Generate 2 gaussian RNs (unit σ , zero mean) from 2 uniform

$$x = \sqrt{-2 \ln(u_2)} \cos(2\pi u_1)$$

$$y = \sqrt{-2 \ln(u_2)} \sin(2\pi u_1)$$

Shifting distribution

- If just need to shift distribution, easy
- $U(a,b): (b-a)^{-1}(u + a)$ where u from $U(0,1)$
- Can similarly shift gaussian distribution from unit, zero-mean gaussian to others

Acceptance/Rejection

- If can't invert your desired distribution $f(x)$, can still generate RN
- Numerically invert (tabulate)
- Or:
 - Generate distribution you can on same domain, $g(x)$
 - Reject numbers with probability $1 - f(x)/g(x)$ (eg, generate random number $u[0, 1]$, x from g ; accept if $u < f(x)/g(x)$)
 - Faster if g tightly bounds f (less rejected guesses)

GSL - Gnu Scientific Library

- Gsl has several good implementations of good PRNGs
- Seperates the generator from the distribution you want

```

#include <stdio.h>
#include <gsl/gsl_rng.h>

int main(int argc, char **argv) {
    gsl_rng *rng;
    int i;
    double u;

    rng = gsl_rng_alloc(gsl_rng_mt19937);
    gsl_rng_set(rng, 1);

    for (i=0; i<100; i++) {
        u = gsl_rng_uniform(rng);
        printf("%d %f\n", i, u);
    }

    gsl_rng_free(rng);

    return 0;
}

```

Create, seed PRNG

Generate Random #s

Clean up

```

$ gcc -o gsl gsl.c -I${SCINET_GSL_INC}
-L${SCINET_GSL_LIB} -lgslcbblas -lgsl

```

Python

- Numpy.random - series of random number generators, distributions.
- Based on mersenne twister
- Good, but would be nice to have choice...

Notes on Seeding

- For random seeds, taking system time is common
- If doing in parallel, need to make sure different processes/ threads have different seeds!
- Factor rank, thread num, pid, etc in there somehow

Homework: I

- Consider the sequence of numbers: 1 followed by 10^7 values of 10^{-7}
- Should Sum to 2
- Write code which sums up those values in order. What answer does it get?
- Add to program routine which sums up values in reverse order. Does it get correct answer?
- How would you get correct answer?
- Submit code, Makefile, text file with answers.

Homework: 2

- Implement an LCG with $a = 106$, $c = 1283$, $m = 6075$ that generates random numbers from $0..1$
- Using that and MT: generate pairs (dx, dy) with dx, dy each in $-1..+1$. Generate histograms of dx and dy (say 200 bins). Look ok? What would you expect variation to be?
- For 10,000 pts: take random walks from $0,0$ until exceed radius of 2, then stop. Plot histogram of final angles for the two PRNGs. What do you see?
- Submit makefile, code, plots, VC log

