The CURAND library

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Outline

Host interface

Device interface

Rejection sampling on the GPU

CURAND

- **CURAND**: a CUDA C library for quickly generating pseudorandom and quasi-random numbers.
- **Pseudorandom sequence**: a sequence of numbers, generated by a deterministic algorithm, that has most of the properties of a truly random sequence.
- **Quasi-random (low-discrepancy) sequence**: a sequence of n-dimensional points, generated by a deterministic sequence, that appear random and appear to fill a region of n-dimensional space evenly.

Host and device APIs

- Host API
  - Include the header, `curand.h`, and link with the `-lcurand` flag at compilation.
  - Calls to number generators happen on the host.
  - With each call, a predetermined number of random draws is generated and then stored for alter use in a kernel call or a copy statement.
  - Supports 3 pseudorandom generators and 4 quasi-random generators.
- Device API
  - Include the header, `curand_kernel.h`, and link with the `-lcurand` flag at compilation.
  - Calls to number generators happen within kernels and device functions.
  - Random numbers are generated and immediately used in real time on an as-need basis.
  - For CUDA version 4.2, supports fewer generator algorithms then the host API.

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Using the host API

1. Create a new generator with `curandCreateGenerator()`.
2. Set the generator options. For example, use `curandSetPseudoRandomGeneratorSeed()` to set the seed.
3. Allocate memory for the random numbers with `cudaMalloc()`.
4. Generate random numbers with on or more calls to `curandGenerate()` or another generation function.
5. Clean up the generator with `curandDestroyGenerator()`.
6. Clean up everything else with `free()` and `cudaFree()`.

Generator types for `curandCreateGenerator()`

- Pseudorandom number generators
  - `CURAND_RNG_PSEUDO_DEFAULT`: XORWOW for the version currently on impact1
  - `CURAND_RNG_PSEUDO_XORWOW`: XORWOW algorithm
  - `CURAND_RNG_PSEUDO_MRG32K3A`: combined multiple recursive family
  - `CURAND_RNG_PSEUDO_MTGP32`: Mersenne Twister family
- Quasi-random number generators
  - `CURAND_RNG_QUASI_DEFAULT`: currently Sobol, 32-bit sequences
  - `CURAND_RNG_QUASI_SOBOL32`: Sobol, 32-bit sequences
  - `CURAND_RNG_QUASI_SOBOL64`: Sobol, 64-bit sequences
  - `CURAND_RNG_QUASI_SCRAMBLED_SOBOL32`: scrambled Sobol, 32-bit sequences
  - `CURAND_RNG_QUASI_SCRAMBLED_SOBOL64`: scrambled Sobol, 62-bit sequences

Generator options

- **Seed**: a 64-bit integer that initializes the starting state of a pseudorandom number generator.
- **Offset**: a parameter used sot skip ahead in the sequence. Set offset = 100 to return the 100th number in the sequence first. Not available for the Mersenne Twister.
- **Order**: a parameter specifying how results are ordered in global memory.

Generator functions

- Random bits:

```
curandStatus_t curandGenerate(curandGenerator_t generator,
     unsigned int *outputPtr, size_t num)
```

- Uniform(0, 1):

```
curandStatus_t curandGenerateUniform(curandGenerator_t generator
     , float *outputPtr, size_t num)

curandStatus_t curandGenerateUniformDouble(curandGenerator_t
     generator, double *outputPtr, size_t num)
```

- Normal:

```
curandStatus_t curandGenerateNormal(curandGenerator_t generator,
      float *outputPtr, size_t n, float mean, float stddev)

curandStatus_t curandGenerateNormalDouble(curandGenerator_t
     generator, double *outputPtr, size_t n, double mean,
     double stddev)
```

Generator functions

- Log-normal:

```
curandStatus_t curandGenerateLogNormal(curandGenerator_t
     generator, float *outputPtr, size_t n, float mean, float
     stddev)

curandStatus_t curandGenerateLogNormalDouble(curandGenerator_t
     generator, double *outputPtr, size_t n, double mean,
     double stddev)
```

Example: host_api.cu

```
/*
* This program uses the host CURAND API to generate 10 pseudorandom floats.
*/

#include <stdio.h>
#include <stdlib.h>
#include <cuda.h>
#include <curand.h>

int main(int argc, char *argv[]){
  size_t n = 10;
  size_t i;
  curandGenerator_t gen;
  float *devData , *hostData;

 /* Allocate n floats on host */
  hostData = (float *) calloc(n, sizeof(float));

  /* Allocate n floats on device */
  cudaMalloc((void **) &devData, n*sizeof(float));

  /* Create a Mersenne Twister pseudorandom number generator */
  curandCreateGenerator(&gen, CURAND_RNG_PSEUDO_MTGP32);

  /* Set seed */
  curandSetPseudoRandomGeneratorSeed(gen, 1234ULL);

  /* Generate n floats on device */
  curandGenerateUniform(gen, devData, n);
```

Example: host_api.cu

```
 /* Copy device memory to host */
  cudaMemcpy(hostData , devData , n * sizeof(float),
        cudaMemcpyDeviceToHost);

  /* Show result */
  printf("Random Unif(0, 1) draws:\n");
  for(i = 0; i < n; i++) {
    printf("  %1.4f\n", hostData[i]);
  }
  printf("\n");

  /* Cleanup */
  curandDestroyGenerator(gen);
  cudaFree(devData);
  free(hostData);
}
```

```
> nvcc host_api.cu -lcurand -o host_api
> ./host_api
Random Unif(0, 1) draws:
  0.5823
  0.4636
  0.6156
  0.9964
  0.1182
  0.2672
  0.9241
  0.7161
  0.2309
  0.4075
```

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Using the Device API

1. Within a kernel, call `curand_init()` to initialize the "state" of the random number generator.
2. Within a (possibly separate) kernel, call `curand()` or one of its wrapper functions (such as `curand_uniform()` or `curand_normal()` to generate pseudorandom or quasi random numbers as needed.

- RNG types available
  - Pseudorandom
    - XORWOW
  - Quasi-random
    - 32-bit Sobol
    - 32-bit scrambled Sobol

Device API functions: XORWOW

```
__device__ void curand_init (unsigned long long seed,
                             unsigned long long sequence,
                             unsigned long long offset,
                             curandState_t *state)

__device__ unsigned int
curand (curandState_t *state) // RANDOM BITS

__device__ float
curand_uniform (curandState_t *state) // U(0,1)

__device__ double
curand_uniform_double (curandState_t *state) // U(0,1)

__device__ float
curand_normal (curandState_t *state) // N(0,1)

__device__ double
curand_normal_double (curandState_t *state) // N(0,1)
```

Device API functions: XORWOW

```
__device__ float2
curand_normal2 (curandState_t *state) // 2 N(0,1) draws

__device__ float2
curand_log_normal2 (curandState_t *state) // 2 N(0,1) draws

__device__ float
curand_log_normal (curandState_t *state, float mean, float stddev)

__device__ double
curand_log_normal_double (curandState_t *state, double mean, double stddev)

__device__ double2
curand_normal2_double (curandState_t *state) // 2 draws

__device__ double2
curand_log_normal2_double (curandState_t *state) // 2 draws
```

Device API functions: Sobol

```
__device__ void
curand_init (
    unsigned int *direction_vectors,
    unsigned int offset,
    curandStateSobol32_t *state) // Sobol

__device__ void
curand_init (
    unsigned int *direction_vectors,
    unsigned int scramble_c,
    unsigned int offset,
    curandStateScrambledSobol32_t *state) // Scrambled Sobol

__device__ unsigned int
curand (curandStateSobol32_t *state)

__device__ float
curand_uniform (curandStateSobol32_t *state)
```

Device API functions: Sobol

```
__device__ float
curand_normal (curandStateSobol32_t *state)

__device__ float
curand_log_normal (
    curandStateSobol32_t *state,
    float mean,
    float stddev)

__device__ double
curand_uniform_double (curandStateSobol32_t *state)

__device__ double
curand_normal_double (curandStateSobol32_t *state)

__device__ double
curand_log_normal_double (
    curandStateSobol32_t *state,
    double mean,
    double stddev)
```

Example: device_api.cu

```
/*
 * This program uses the device CURAND API to calculate what
 * proportion of pseudo-random ints are odd.
 */

#include <stdio.h>
#include <stdlib.h>
#include <cuda.h>
#include <curand_kernel.h>

__global__ void setup_kernel(curandState *state){
  int id = threadIdx.x + blockIdx.x * 64;

  /* Each thread gets same seed, a different sequence number , no offset */
  curand_init(1234, id, 0, &state[id]);
}

__global__ void generate_kernel(curandState *state, int *result){
  int id = threadIdx.x + blockIdx.x * 64; int count = 0;
  unsigned int x;

  /* Copy state to local memory for efficiency */
  curandState localState = state[id];

  /* Generate pseudo -random unsigned ints */
  for(int n = 0; n < 100000; n++){
    x = curand(&localState);
```

Example: device_api.cu

```
    /* Check if odd */
    if(x & 1){
      count ++;
    }
  }

  /* Copy state back to global memory */
  state[id] = localState;

  /* Store results */
  result[id] += count;
}

int main(int argc, char *argv[]){
  int i, total;

  int *devResults, *hostResults;
  curandState *devStates;

  /* Allocate space for results on host */
  hostResults = (int *) calloc(64 * 64, sizeof(int));

  /* Allocate space for results on device */
  cudaMalloc((void **)&devResults , 64 * 64 *sizeof(int));

  /* Set results to 0 */
  cudaMemset(devResults , 0, 64 * 64 * sizeof(int));

  /* Allocate space for prng states on device */
  cudaMalloc((void **)&devStates , 64 * 64 * sizeof(curandState));
```

Example: device_api.cu

```
  /* Setup prng states */
  setup_kernel<<<64, 64>>>(devStates);

  /* Generate and use pseudorandom numbers*/
  for(i = 0; i < 10; i++){
    generate_kernel<<<64, 64>>>(devStates, devResults);
  }

  /* Copy device memory to host */
  cudaMemcpy(hostResults, devResults , 64 * 64 * sizeof(int),
        cudaMemcpyDeviceToHost);

  /* Show result */
  total = 0;
  for(i = 0; i < 64 * 64; i++) {
    total += hostResults[i];
  }
  printf("Fraction odd was %10.13f\n", (float) total / (64.0f * 64.0f
        * 100000.0f * 10.0f));

  /* Cleanup */
  cudaFree(devStates);
  cudaFree(devResults);
  free(hostResults);

  return EXIT_SUCCESS;
}
```

Example: device_api.cu

```
> nvcc device_api.cu -lcurand -o device_api
ptxas /tmp/tmpxft_000020d0_00000000-2_device_api.pts, line 501;
  warning : Double is not supported. Demoting to float.
>
> ./device_api
Fraction odd was 0.4999966323376
```

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RNG types supported

- Dr. Jarad Niemi wrote example rejection sampling code available at `https://github.com/jarad/gpuRejectionSampling`.
- Idea
  1. Draw a pseudorandom number, x.
  2. If x is too big, throw out x and return to step 1.
  3. Return x.

cpu_runif.c

```c
#include <Rmath.h>
//#include <stdlib.h>


int cpu_runif(int n, double ub, int ni, int nd, double *u, int *count)
{
    int i, j, a;
    double b;
    GetRNGstate();
    for (i=0;i<n;i++) {
        count[i] = -1;
        u[i] = ub+1;

        while ( u[i]>ub  ) {
            count[i]++;
            //u[i] = rand()/((double)RAND_MAX + 1);
            u[i] = runif(0,1);

            // Computational overhead
            a=0; for (j=0; j<ni; j++) a += 1;
            b=1; for (j=0; j<nd; j++) b *= 1.00001;
        }
    }
    PutRNGstate();
}

void cpu_runif_wrap(int *n, double *ub, int *ni, int *nd, double *u, int *count){
    cpu_runif(*n, *ub, *ni, *nd, u, count);
}
```

gpu_runif.cu

```
#include <curand_kernel.h>
#include "cutil_inline.h"

#define THREADS_PER_BLOCK 256

__global__ void setup_prng(unsigned long long seed, curandState *state)
{
    int id = threadIdx.x + blockIdx.x * THREADS_PER_BLOCK;
    curand_init(seed, id, 0, &state[id]);
}

__global__ void runif_kernel(curandState *state, double ub, int ni, int nd,
                             double *uniforms, int *counts)
{
    int i, a, count, id = threadIdx.x + blockIdx.x * THREADS_PER_BLOCK;
    double b, u;

    // Copy state to local memory for efficiency */
    curandState localState = state[id];

    // Find random uniform below the upper bound
    count  = -1;
    u = ub+1;
```

gpu_runif.cu

```
 while ( u>ub )
    {
        count++;
        u = curand_uniform_double(&localState);

        // Computational overhead
        a=0; for (i=0; i<ni; i++) a += 1;
        b=1; for (i=0; i<nd; i++) b *= 1.00001;
    }

    // Copy state back to global memory */
    state[id] = localState ;

    // Store results */
    uniforms[id] = u;
    counts[id] = count;
}

//CURAND_RNG_PSEUDO_MTGP32

extern "C" {

void gpu_runif(int *n, double *ub, int *ni, int *nd, double *seed, double *u, int *c)
{
    int nBlocks = *n/THREADS_PER_BLOCK, *d_c;
    size_t u_size = *n *sizeof(double), c_size = *n *sizeof(int);
    double *d_u;

    cutilSafeCall( cudaMalloc((void**)&d_u,  u_size) );
    cutilSafeCall( cudaMalloc((void**)&d_c,  c_size) );
```

gpu_runif.cu

```
    // Setup prng states
    curandState *d_states;
    cutilSafeCall( cudaMalloc((void**)&d_states, nBlocks*THREADS_PER_BLOCK*sizeof(curandState)) );
    setup_prng<<<nBlocks,THREADS_PER_BLOCK>>>(*seed, d_states);

    runif_kernel<<<nBlocks,THREADS_PER_BLOCK>>>(d_states, *ub, *ni, *nd, d_u, d_c);

    cutilSafeCall( cudaMemcpy(u,   d_u,   u_size, cudaMemcpyDeviceToHost) );
    cutilSafeCall( cudaMemcpy(c,   d_c,   c_size, cudaMemcpyDeviceToHost) );

    cutilSafeCall( cudaFree(d_u)      );
    cutilSafeCall( cudaFree(d_c)      );
    cutilSafeCall( cudaFree(d_states) );
}

} // end of extern "C"
```

my.unif.r

```
my.runif = function(n, ub, ni=1, nd=1,
                      engine="R", seed=1)
{
    engine = pmatch(engine, c("R","C","GPU"))

    switch(engine,
    {
        # R implementation
        u = rep(Inf,n)
        count = rep(0,n)
        set.seed(seed)

        for (i in 1:n) while( (u[i] <- runif(1))>ub )
        {
            count[i] = count[i]+1
            a = 0
            b = 1
            for (j in 1:ni) a = a + 1
            for (j in 1:nd) b = b * 1.00001
        }
        return(list(u=u,count=count))
    },
```

my.unif.r

```
   {
        # C implementation
        set.seed(seed)
        out = .C("cpu_runif_wrap",
                      as.integer(n),
                      as.double(ub),
                      as.integer(ni),
                      as.integer(nd),
                      u=double(n),
                      count=integer(n))
        return(list(u=out$u,count=out$count))
    },
    {
        # GPU implementation
        out = .C("gpu_runif", as.integer(n), as.double(ub),
                              as.integer(ni), as.integer(nd),
                              as.double(seed),
                              u=double(n), count=integer(n))
        return(list(u=out$u,count=out$count))
    })
}
```

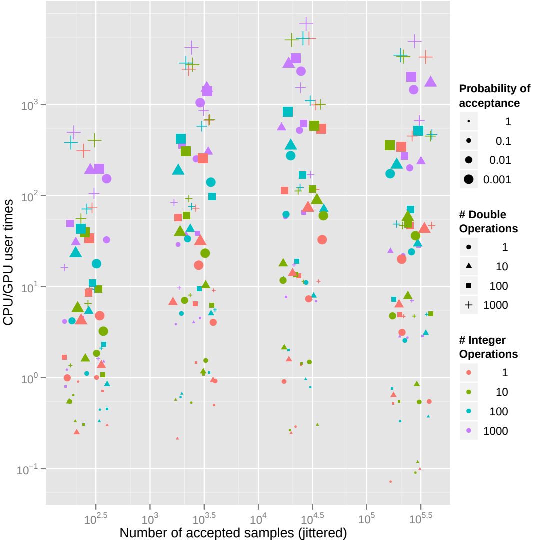
Running the example

- The files, `comparison.r` and `comparison-analysis.r`, compare the performances of the R, C, and GPU rejection samplers.

```
> ls
demo  inst  R  README.md  src
> cd src
> make
/usr/local/cuda/bin/nvcc -arch=sm_20  -c -I. -I/usr/local/include -I/
      usr/local/cuda/include -I/apps/lib64/R/include -I/usr/local/
      NVIDIA_GPU_Computing_SDK/C/common/inc -Xcompiler -fpic -DRPRINT
      -DNDEBUG cpu_runif.c -o cpu_runif.o
...

> cd ..
> ls
demo  inst  R  README.md  src
> cd demo
> ls
comparison.R      comparison-analysis.R      segfault.R
> R CMD BATCH comparison.R & # do this using screen: it takes a
      couple days unless you modify comparison.R
> R CMD BATCH comparison-analysis.R
> ls
comparison-analysis.R     comparison.csv   comparison.Rout   rejection.
      pdf   segfault.R
comparison-analysis.Rout  comparison.R     comparison.tex    Rplots.pdf
            sm.tex
```

Performance: ratios of CPU time to GPU time



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Resources

- Guides:
  1. CURAND Guide
- Code from today:
  - host_api.cu
  - device_api.cu
  - Dr. Niemi's rejection sampling code

That's all for today.

- Series materials are available at `http://will-landau.com/gpu`.