Sunway TaihuLight Programming By examples

The Codesign Team, RIKEN AICS

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Abstract

Sunway TaihuLight is the supercomputer with the largest peak performance on the Earth at the moment. We would like to understand what kind of application can be executed on TaihuLight, what are the theoretical limits of the performance of those applications, and how the actual implementations achieve closer to the theoretically-given performance limits.

The architecture of Sunway TaihuLight is different from those of modern computers. Many of modern computers have multi-level memory hierarchy, such as: the L1, L2, L3 cache, and the main memory. On the contrary, Sunway TaihuLight has only two levels of memory: the local directive memory (LDM) is the only memory layer above the main memory. The core group (CG) consists of 64 computing processor element (CPEs) organized in 8x8 mesh.

These architectures pose unique challenge in the optimization on Sunway TaihuLight. On the other hand, they provide high performance if we are able to understand the architectures and use them in the right way.

Therefore, we summarize the knowledge for using the Sunway TaihuLight in this document, by collecting the set of source codes for Sunway TaihuLight and their execution and benchmark results.

Contents

1　練習編

1.1　練習編の概要

練習編では、Sunway TaihuLight のプログラミングに必要なプリミティブを順次取り上げ、実際に動くプログラムを作りながら動作を確認していく。

1.2　Hello World

1.2.1　Introduction

One of the most simple way of programming Sunway TaihuLight is to use only the MPE (Management Processing Element). The MPE can be programmed in vanilla C/C++. Let us first write some program that run on MPE.

1.2.2　Source code

We have compiled and executed the following source codes:

`master.c`

```
#include <stdio.h>
#include <athread.h>
#include <fcntl.h>
#define N 4096


//extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  for (i=0; i<N;++i){
    c[i] = a[i] * b[i];
  }

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }

  return 0;
}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/01-master/src/
make && make run
```

1.2.3 Results

Got the following results:

```
# 2017-02-15 00:20:49.556760
$ chmod 755 /home/nushio/hub/GB17/sunway-test/01-master/src/run.sh
$ ssh sunway 'mkdir -p /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test
$ rsync -avz /home/nushio/hub/GB17/sunway-test/01-master/src/ sunway:/home/export/base/nsccwuxi_rike
sending incremental file list
./
Makefile
run.sh

sent 436 bytes  received 72 bytes  145.14 bytes/sec
total size is 955  speedup is 1.88
$ ssh sunway /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/01-master
make: 'all' に対して行うべき事はありません.
bsub -I -b -q q_sw_expr -n 1 -cgsp 64 -share_size 4096 -host_stack 128 ./main.out
Job <6419562> has been submitted to queue <q_sw_expr>
waiting for dispatch ...
hello Sunway TaihuLight
1^2 == 1.000000
3^2 == 9.000000
7^2 == 49.000000
15^2 == 225.000000
31^2 == 961.000000
63^2 == 3969.000000
127^2 == 16129.000000
255^2 == 65025.000000
511^2 == 261121.000000
1023^2 == 1046529.000000
2047^2 == 4190209.000000
4095^2 == 16769025.000000
dispatching ...
Job 6419562 has been finished.
```

1.2.4 Discussion

We have programmed MPE.

1.3 The use of the CPE

1.3.1 Introduction

The most of the computational power of Sunway TaihuLight resides in the CPE(Computing Processing Element)s in the CG(core group)s.

The MPE programs and the CPE programs must be compiled with the `-host` flag and the `-slave` flag, respectively.

A `-hybrid` flag is required when linking.

We use the following syntax to declare a CPE function in the MPE program:

```
extern SLAVE_FUN(func)();
```

And call it via `athread_spawn`

```
athread_spawn(func,0);
athread_join();
```

The second argument, `void *arg` of the `athread_spawn` is the functional argument to `func`.

Use `athread_get` and `athread_put` to communicate data between the MPE and the CPE.

1.3.2 Source code

We have compiled and executed the following source codes:

`master.c`

```
#include <stdlib.h>
#include <stdio.h>
#include <athread.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#define N 4096


extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  // for (i=0; i<N;++i){
  //   c[i] = a[i] * b[i];
  // }
  athread_init();
  athread_spawn(func,0);//fflush(NULL);
  athread_join();

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }
  athread_halt();
  return 0;
}
```

slave.c

```
#include <slave.h>
#include <math.h>
#include <dma.h>

#define N 4096
#define I 64

__thread_local volatile unsigned long get_reply, put_reply;
__thread_local int my_id;
__thread_local double a_slave[I], b_slave[I], c_slave[I];
extern double a[N], b[N], c[N];

void func() {
  int i;
  my_id = athread_get_id(-1);
  get_reply = 0;

  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  for(i=0;i<I;i++){
    c_slave[i]=a_slave[i]*b_slave[i];
  }

  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/02-slave/src/
make && make run
```

1.3.3 Results

Got the following results:

```
# 2017-02-14 20:29:33.736609
$ chmod 755 /home/nushio/hub/GB17/sunway-test/02-slave/src/run.sh
$ ssh sunway 'mkdir -p /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test
$ rsync -avz /home/nushio/hub/GB17/sunway-test/02-slave/src/ sunway:/home/export/base/nsccwuxi_riken
sending incremental file list
./
Makefile
master.c
run.sh
slave.c

sent 1,298 bytes  received 98 bytes  146.95 bytes/sec
total size is 1,995  speedup is 1.43
$ ssh sunway /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/02-slave/
sw5cc.new -O3 -msimd -host -E master.c > master.e
#        sw5cc.new -O3 -msimd -host -s master.c -o master.s
sw5cc.new -O3 -msimd -host -c master.c -o master.o
sw5cc.new -O3 -msimd -slave -E slave.c > slave.e
#sw5cc.new -O3 -msimd -slave -s slave.c -o slave.s
sw5cc.new -O3 -msimd -slave -c slave.c -o slave.o
sw5cc.new -hybrid  master.o slave.o -o main.out
bsub -I -b -q q_sw_expr -n 1 -cgsp 64 -share_size 4096 -host_stack 128 ./main.out
Job <6419252> has been submitted to queue <q_sw_expr>
some node is sleeping, waiting for dispatch ...
hello Sunway TaihuLight
1^2 == 1.000000
3^2 == 9.000000
7^2 == 49.000000
15^2 == 225.000000
31^2 == 961.000000
63^2 == 3969.000000
127^2 == 16129.000000
255^2 == 65025.000000
511^2 == 261121.000000
1023^2 == 1046529.000000
2047^2 == 4190209.000000
4095^2 == 16769025.000000
```

```
dispatching ...
Job 6419252 has been finished.

```

1.3.4 Discussion

We have created a program that uses both the MPE and the CPEs.

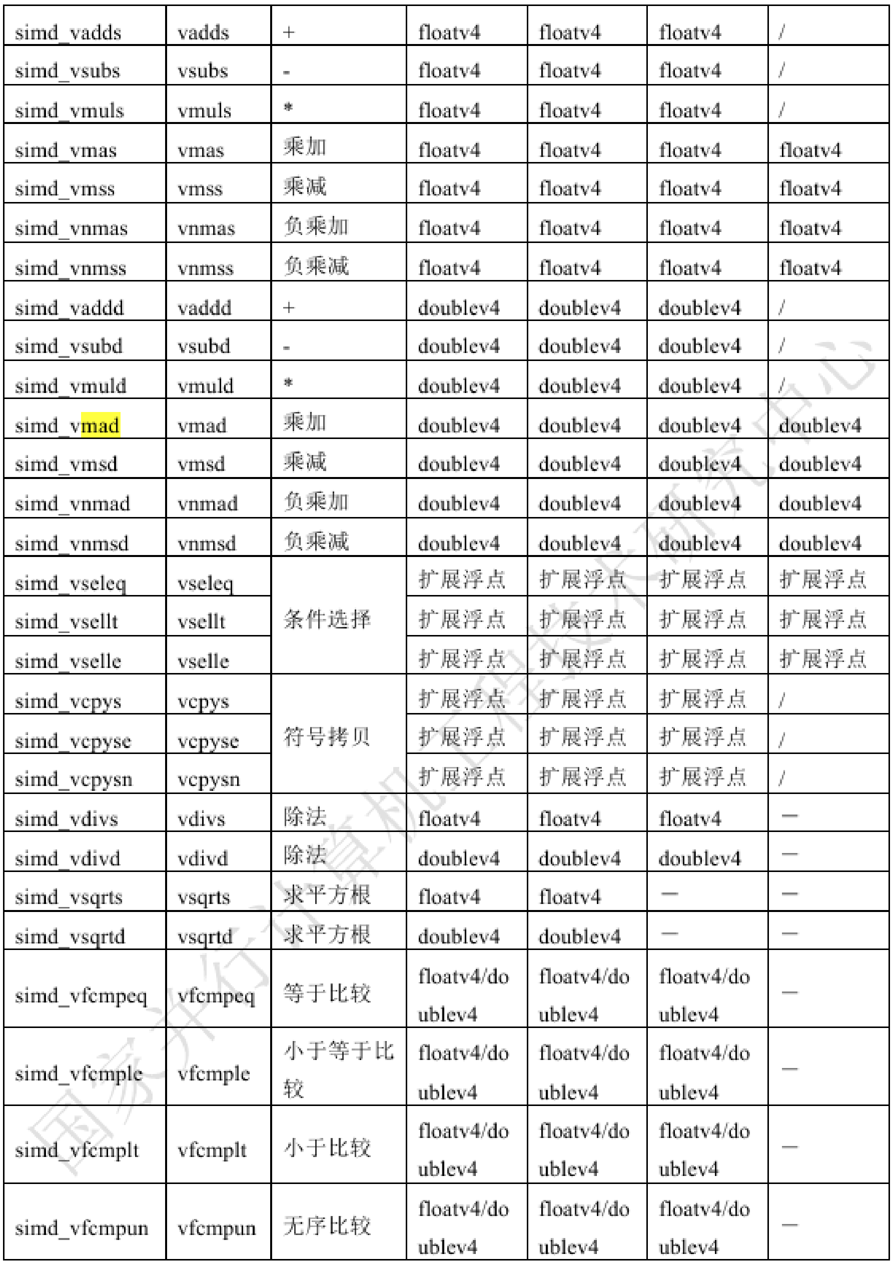
1.4 Using SIMD types

1.4.1 Introduction

We need to use the SIMD intrinsics of Sunway TaihuLight to make use of its full computing potential. The SIMD intrinsic expressions accept SIMD types such as `intv8`, `doublev4`, `floatv4`.

In order to convert between scalar types and SIMD types, for example `double` → `doublev4`, you may use the dedicated intrinsic functions such as `simd_load`, `simd_loadu`. You can also convert between scalar types and SIMD types by simply pointing `double *` and `doublev4 *` to the same address. This works just fine.

We can express computations of SIMD type variables either by the overloaded arithmetic operators, or by using SIMD intrinsic functions such as `simd_vmad`.



simd_vadds	vadds	+	floatv4	floatv4	floatv4	/
simd_vsubs	vsubs	-	floatv4	floatv4	floatv4	/
simd_vmuls	vmuls	*	floatv4	floatv4	floatv4	/
simd_vmas	vmas	乘加	floatv4	floatv4	floatv4	floatv4
simd_vmss	vmss	乘减	floatv4	floatv4	floatv4	floatv4
simd_vnmas	vnmas	负乘加	floatv4	floatv4	floatv4	floatv4
simd_vnmss	vnmss	负乘减	floatv4	floatv4	floatv4	floatv4
simd_vaddd	vaddd	+	doublev4	doublev4	doublev4	/
simd_vsubd	vsubd	-	doublev4	doublev4	doublev4	/
simd_vmuld	vmuld	*	doublev4	doublev4	doublev4	/
simd_vmad	vmad	乘加	doublev4	doublev4	doublev4	doublev4
simd_vmsd	vmsd	乘减	doublev4	doublev4	doublev4	doublev4
simd_vnmad	vnmad	负乘加	doublev4	doublev4	doublev4	doublev4
simd_vnmsd	vnmsd	负乘减	doublev4	doublev4	doublev4	doublev4
simd_vseleq	vseleq	条件选择	扩展浮点	扩展浮点	扩展浮点	扩展浮点
simd_vsellt	vsellt		扩展浮点	扩展浮点	扩展浮点	扩展浮点
simd_vselle	vselle		扩展浮点	扩展浮点	扩展浮点	扩展浮点
simd_vcpys	vcpys	符号拷贝	扩展浮点	扩展浮点	扩展浮点	/
simd_vcpyse	vcpyse		扩展浮点	扩展浮点	扩展浮点	/
simd_vcpysn	vcpysn		扩展浮点	扩展浮点	扩展浮点	/
simd_vdivs	vdivs	除法	floatv4	floatv4	floatv4	—
simd_vdivd	vdivd	除法	doublev4	doublev4	doublev4	—
simd_vsqrts	vsqrts	求平方根	floatv4	floatv4	—	—
simd_vsqrtd	vsqrtd	求平方根	doublev4	doublev4	—	—
simd_vfcmpeq	vfcmpeq	等于比较	floatv4/doublev4	floatv4/doublev4	floatv4/doublev4	—
simd_vfcmple	vfcmple	小于等于比较	floatv4/doublev4	floatv4/doublev4	floatv4/doublev4	—
simd_vfcmplt	vfcmplt	小于比较	floatv4/doublev4	floatv4/doublev4	floatv4/doublev4	—
simd_vfcmpun	vfcmpun	无序比较	floatv4/doublev4	floatv4/doublev4	floatv4/doublev4	—

1.4.2 Source code

We have compiled and executed the following source codes:

`param.h`

```
#define N 4096
#define I 64
#define Iv4 16
```

master.c

```
#include <stdlib.h>
#include <stdio.h>
#include <athread.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#include "param.h"

extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  // for (i=0; i<N;++i){
  //   c[i] = a[i] * b[i];
  // }
  athread_init();
  athread_spawn(func,0);//fflush(NULL);
  athread_join();

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }
  athread_halt();
  return 0;
}
```

slave.c

```
#include <slave.h>
#include <math.h>
#include <dma.h>

#include "param.h"

__thread_local volatile unsigned long get_reply, put_reply;
__thread_local doublev4 a_slave[Iv4], b_slave[Iv4], c_slave[Iv4];
extern double a[N], b[N], c[N];
```

```
void func() {
  int i;
  int my_id = athread_get_id(-1);
  int cid = my_id%8, rid = my_id/8;

  get_reply = 0;

  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  for(i=0;i<Iv4;i++){
    c_slave[i]=a_slave[i]*b_slave[i];
  }

  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/03-slave-vector/src
make && make run
```

1.4.3 Results

Got the following results:

```
# 2017-02-14 13:05:28.457861
$ chmod 755 /home/nushio/hub/GB17/sunway-test/03-slave-vector/src/run.sh
$ ssh sunway 'mkdir -p /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test
$ rsync -avz /home/nushio/hub/GB17/sunway-test/03-slave-vector/src/ sunway:/home/export/base/nsccwux
sending incremental file list
./
Makefile
master.c
param.h
run.sh
slave.c

sent 1,385 bytes  received 117 bytes  429.14 bytes/sec
total size is 2,064  speedup is 1.37
$ ssh sunway /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/03-slave-
sw5cc.new -O3 -msimd -host -E master.c > master.e
```

```
#        sw5cc.new -O3 -msimd -host -s master.c -o master.s
sw5cc.new -O3 -msimd -host -c master.c -o master.o
sw5cc.new -O3 -msimd -slave -E slave.c > slave.e
#sw5cc.new -O3 -msimd -slave -s slave.c -o slave.s
sw5cc.new -O3 -msimd -slave -c slave.c -o slave.o
sw5cc.new -hybrid  master.o slave.o -o main.out
bsub -I -b -q q_sw_expr -n 1 -cgsp 64 -share_size 4096 -host_stack 128 ./main.out
Job <6418407> has been submitted to queue <q_sw_expr>
some node is sleeping, waiting for dispatch ...
hello Sunway TaihuLight
1^2 == 1.000000
3^2 == 9.000000
7^2 == 49.000000
15^2 == 225.000000
31^2 == 961.000000
63^2 == 3969.000000
127^2 == 16129.000000
255^2 == 65025.000000
511^2 == 261121.000000
1023^2 == 1046529.000000
2047^2 == 4190209.000000
4095^2 == 16769025.000000
dispatching ...
Job 6418407 has been finished.
```

1.4.4 Discussion

We heve rewritten the previous example using SIMD types and SIMD operations.

1.5 Communicating between CPEs

1.5.1 Introduction

CPEs form an 8x8 array, and we can send the data in the row or the column direction in the CPE array.

The intrinsic functions `simd_putr` and `simd_putc` are used to send the data in the row nad the column direction, while `simd_getr` and `simd_getc` are used to recieve the data.

The second argument to the `simd_putr` and `simd_putc` functions is the destination address. The address can be one of (0...7) which specifies a column/row. The address can also be 8, which means a broadcast.

1.5.2 Source code

We have compiled and executed the following source codes:

`param.h`

```
#define N 256
#define I 4
```

```
#define Iv4 1
```

master.c

```
#include <stdlib.h>
#include <stdio.h>
#include <athread.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#include "param.h"

extern SLAVE_FUN(move_r)();
extern SLAVE_FUN(move_c)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  athread_init();

  for (i=0; i<N;++i){
    a[i] = i/4;
    b[i] = i/4;
  }

  printf("before:");
  for (i=0; i<N; i++){
    if(i%4==0) printf(" ");
    if(i%32==0) printf("\n");
    printf("%2.0lf", a[i]);
  }
  printf("\n");

  athread_spawn(move_r,0);
  athread_join();

  printf("after move_r:");
  for (i=0; i<N; i++){
    if(i%4==0) printf(" ");
    if(i%32==0) printf("\n");
    printf("%2.0lf", c[i]);
  }
  printf("\n");

  athread_spawn(move_c,0);
  athread_join();
  printf("after move_c:");
  for (i=0; i<N; i++){
    if(i%4==0) printf(" ");
    if(i%32==0) printf("\n");
    printf("%2.0lf", c[i]);
  }
  printf("\n");

  athread_halt();
  return 0;
}
```

slave.c

```
#include <slave.h>
#include <math.h>
#include <dma.h>

#include "param.h"

__thread_local volatile unsigned long get_reply, put_reply;
__thread_local doublev4 a_slave[Iv4], b_slave[Iv4], c_slave[Iv4];
extern double a[N], b[N], c[N];

void move_r() {
  int i;
  int my_id = athread_get_id(-1);
  int cid = my_id%8, rid = my_id/8;

  get_reply = 0;

  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  simd_putr(a_slave[0], (cid+1)%8);
  c_slave[0] = simd_getr(c_slave[0]);

  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}

void move_c() {
  int i;
  int my_id = athread_get_id(-1);
  int cid = my_id%8, rid = my_id/8;

  get_reply = 0;
  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  simd_putc(b_slave[0], (rid*3)%8);
  c_slave[0] = simd_getc(c_slave[0]);

  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/04-slave-comm/src/
make && make run
```

1.5.3 Results

Got the following results:

```
# 2017-02-15 00:36:05.867609
$ chmod 755 /home/nushio/hub/GB17/sunway-test/04-slave-comm/src/run.sh
$ ssh sunway 'mkdir -p /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test
$ rsync -avz /home/nushio/hub/GB17/sunway-test/04-slave-comm/src/ sunway:/home/export/base/nsccwuxi_
sending incremental file list
./
master.c
run.sh

sent 532 bytes  received 78 bytes  135.56 bytes/sec
total size is 2,906  speedup is 4.76
$ ssh sunway /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/04-slave-
sw5cc.new -O3 -msimd -host -E master.c > master.e
#       sw5cc.new -O3 -msimd -host -s master.c -o master.s
sw5cc.new -O3 -msimd -host -c master.c -o master.o
sw5cc.new -hybrid  master.o slave.o -o main.out
bsub -I -b -q q_sw_expr -n 1 -cgsp 64 -share_size 4096 -host_stack 128 ./main.out
Job <6419585> has been submitted to queue <q_sw_expr>
waiting for dispatch ...
before:
 0 0 0 0  1 1 1 1  2 2 2 2  3 3 3 3  4 4 4 4  5 5 5 5  6 6 6 6  7 7 7 7
 8 8 8 8  9 9 9 9 10101010 11111111 12121212 13131313 14141414 15151515
16161616 17171717 18181818 19191919 20202020 21212121 22222222 23232323
24242424 25252525 26262626 27272727 28282828 29292929 30303030 31313131
32323232 33333333 34343434 35353535 36363636 37373737 38383838 39393939
```

```
40404040 41414141 42424242 43434343 44444444 45454545 46464646 47474747
48484848 49494949 50505050 51515151 52525252 53535353 54545454 55555555
56565656 57575757 58585858 59595959 60606060 61616161 62626262 63636363
after move_r:
 7 7 7 7  0 0 0 0  1 1 1 1  2 2 2 2  3 3 3 3  4 4 4 4  5 5 5 5  6 6 6 6
15151515  8 8 8 8  9 9 9 9 10101010 11111111 12121212 13131313 14141414
23232323 16161616 17171717 18181818 19191919 20202020 21212121 22222222
31313131 24242424 25252525 26262626 27272727 28282828 29292929 30303030
39393939 32323232 33333333 34343434 35353535 36363636 37373737 38383838
47474747 40404040 41414141 42424242 43434343 44444444 45454545 46464646
55555555 48484848 49494949 50505050 51515151 52525252 53535353 54545454
63636363 56565656 57575757 58585858 59595959 60606060 61616161 62626262
after move_c:
 0 0 0 0  1 1 1 1  2 2 2 2  3 3 3 3  4 4 4 4  5 5 5 5  6 6 6 6  7 7 7 7
24242424 25252525 26262626 27272727 28282828 29292929 30303030 31313131
48484848 49494949 50505050 51515151 52525252 53535353 54545454 55555555
 8 8 8 8  9 9 9 9 10101010 11111111 12121212 13131313 14141414 15151515
32323232 33333333 34343434 35353535 36363636 37373737 38383838 39393939
56565656 57575757 58585858 59595959 60606060 61616161 62626262 63636363
16161616 17171717 18181818 19191919 20202020 21212121 22222222 23232323
40404040 41414141 42424242 43434343 44444444 45454545 46464646 47474747
dispatching ...
Job 6419585 has been finished.
```

1.5.4 Discussion

We have confirmed that `simd_putr` sends the data in the row direction, and `simd_putc` sends the data in the column direction.

1.6 SIMD arithmetic instructions (TODO)

1.6.1 Introduction

We need to use the SIMD intrinsics of Sunway TaihuLight to make use of its full computing potential. The SIMD intrinsic expressions accept SIMD types such as `intv8`, `doublev4`, `floatv4`.

We will test the effects of the SIMD intrinsics.

1.6.2 Source code

We have compiled and executed the following source codes:

`param.h`

```
#define N 4096
#define I 64
#define Iv4 16
```

`master.c`

```
#include <stdlib.h>
#include <stdio.h>
#include <athread.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#include "param.h"

extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  // for (i=0; i<N;++i){
  //   c[i] = a[i] * b[i];
  // }
  athread_init();
  athread_spawn(func,0);//fflush(NULL);
  athread_join();

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }
  athread_halt();
  return 0;
}
```

slave.c

```
#include <slave.h>
#include <math.h>
#include <dma.h>

#include "param.h"

__thread_local volatile unsigned long get_reply, put_reply;
__thread_local doublev4 a_slave[Iv4], b_slave[Iv4], c_slave[Iv4];
extern double a[N], b[N], c[N];
```

```
void func() {
  int i;
  int my_id = athread_get_id(-1);
  int cid = my_id%8, rid = my_id/8;

  get_reply = 0;

  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  for(i=0;i<Iv4;i++){
    c_slave[i]=a_slave[i]*b_slave[i];
  }

  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/05-slave-sqrt/src/
make && make run
```

1.6.3 Results

Got the following results:

```
# 2017-02-15 13:46:19.548559
$ chmod 755 /home/nushio/hub/FDPS/sandbox/nushio_box/sunway-test/05-slave-sqrt/src/run.sh
$ ssh sunway 'mkdir -p /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test
$ rsync -avz /home/nushio/hub/FDPS/sandbox/nushio_box/sunway-test/05-slave-sqrt/src/ sunway:/home/ex
sending incremental file list
run.sh

sent 173 bytes  received 40 bytes  28.40 bytes/sec
total size is 2,062  speedup is 9.68
$ ssh sunway /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/05-slave-
sw5cc.new -O3 -msimd -host -E master.c > master.e
#       sw5cc.new -O3 -msimd -host -s master.c -o master.s
sw5cc.new -O3 -msimd -host -c master.c -o master.o
sw5cc.new -O3 -msimd -slave -E slave.c > slave.e
#sw5cc.new -O3 -msimd -slave -s slave.c -o slave.s
sw5cc.new -O3 -msimd -slave -c slave.c -o slave.o
sw5cc.new -hybrid  master.o slave.o -o main.out
```

```
bsub -I -b -q q_sw_expr -n 1 -cgsp 64 -share_size 4096 -host_stack 128 ./main.out
Job <6420164> has been submitted to queue <q_sw_expr>
waiting for dispatch ...
hello Sunway TaihuLight
1^2 == 1.000000
3^2 == 9.000000
7^2 == 49.000000
15^2 == 225.000000
31^2 == 961.000000
63^2 == 3969.000000
127^2 == 16129.000000
255^2 == 65025.000000
511^2 == 261121.000000
1023^2 == 1046529.000000
2047^2 == 4190209.000000
4095^2 == 16769025.000000
dispatching ...
Job 6420164 has been finished.
```

1.6.4 Discussion

TODO

1.7 Using the C++ compiler

1.7.1 Introduction

You can use C++ compiler in TaihuLight.

1.7.2 Source code

We have compiled and executed the following source codes:

`master.cpp`

```
#include <stdlib.h>
#include <stdio.h>
#include <athread.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#define N 4096


extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  // for (i=0; i<N;++i){
  //   c[i] = a[i] * b[i];
  // }
  athread_init();
  athread_spawn(func,0);//fflush(NULL);
  athread_join();

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }
  athread_halt();
  return 0;
}
```

slave.c

```
#include <slave.h>
#include <math.h>
#include <dma.h>

#define N 4096
#define I 64

__thread_local volatile unsigned long get_reply, put_reply;
__thread_local int my_id;
__thread_local double a_slave[I], b_slave[I], c_slave[I];
extern double a[N], b[N], c[N];

void func() {
  int i;
  my_id = athread_get_id(-1);
  get_reply = 0;

  athread_get(PE_MODE, &a[my_id*I], &a_slave[0],I*8,&get_reply,0,0,0);
  athread_get(PE_MODE, &b[my_id*I], &b_slave[0],I*8,&get_reply,0,0,0);
  while(get_reply!=2) {}

  for(i=0;i<I;i++){
    c_slave[i]=a_slave[i]*b_slave[i];
  }
  put_reply=0;
  athread_put(PE_MODE,&c_slave[0],&c[my_id * I],I*8,&put_reply,0,0);
  while(put_reply!=1) {}

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/02-slave/src/
make && make run
```

1.7.3 Results

Got the following results:

```
TODO
```

1.7.4 Discussion

TODO

2 実践編

2.1 実践編の概要

実践編では、Sunway TaihuLight である程度まとまったプログラムを作っていく。具体的には、村主の担当分野である Temporal Blocking をかけたステンシルアプリケーションを主に作りながら、TaihuLight でどうすれば性能が出るかを検証していく。

2.2 1CG (Core Group) での Temporal Blocking 実験

2.2.1 Introduction

Sunway での研究開発の方針として、まずは簡単な差分ステンシルを用い、1CG で temporal blocking で性能を出すことがそもそも可能かどうかを確認してみることにする。

ここでの「性能を出す」とは、ローカルメモリサイズ、主記憶バンド幅から理論的に可能な性能に比べて何%の演算性能が実現可能かを確認するということである。

この実験は 1 プロセスで行うので並列化とか通信は考えないでやることができて、実際、少し規模が大きい問題を考えるとノード間通信の時間はほぼ無視できるので通信と計算を無理にオーバーラップさせる必要はなくなる。もっとも定量的、実験的にちゃんと見積もっておく必要はある。

この実験で駄目なら何やっても駄目だし、これでできるなら基本には同じやり方でコード生成できれば色々他のことができることになる。

2.2.2 理論的に実現可能な演算性能の見積もり

理論的に実現可能な演算性能は以下のように見積もられる。

演算器の演算性能および主記憶の帯域幅を F Flop/s および B Byte/s とする。またステンシル計算の1メッシュあたりの演算量および、独立変数の情報量を C Flop, H Byte とする。

すると、Spatial Blocking をもちいる場合、1秒間に更新可能なメッシュ数 n_{up} は、

$$n_{up} = \min\left(\frac{B}{2H}, \frac{F}{C}\right) \tag{1}$$

で見積もられる。そして、実効性能は

$$\begin{aligned} F_{up} &= C \cdot n_{up} && (2)\\ &= \min\left(\frac{BC}{2H}, F\right) && (3) \end{aligned}$$

で見積もられる。

Temporal Blocking をもちいる場合、1秒間に更新可能なメッシュ数 n_{up} は、キャッシュに当てたタイルサイズを N_T、空間の次元を d、ステンシルの袖領域のサイズを N_s として

$$n_{up} = \min\left(\frac{N_T B}{4dN_s H}, \frac{F}{C}\right) \tag{4}$$

で見積もられる。そして、実効性能は

$$\begin{aligned} F_{up} &= C \cdot n_{up} && (5)\\ &= \min\left(\frac{N_T BC}{4dN_s H}, F\right) && (6) \end{aligned}$$

で見積もられる。

2.2.3 Source code

We have compiled and executed the following source codes:

`param.h`

```
#define NX 50
#define NY 50
#define NZ 50

```

```
#define SX 34
#define SY 34
#define SZ 34

#define T_MAX 3000

typedef double Real;


const Real Fu = 1.0/86400, Fv = 6.0/86400, Fe = 1.0/900, Du = 0.1*2.3e-9, Dv = 12.2e-11;
const Real dt = 0*200, dx = 0.001;
```

master.c

```
#include <stdio.h>
#include <athread.h>
#include <fcntl.h>
#define N 4096


//extern SLAVE_FUN(func)();

double a[N];
double b[N];
double c[N];

int main() {
  int i;
  printf("hello Sunway TaihuLight\n");

  for (i=0; i<N;++i){
    a[i] = i;
    b[i] = i;
  }

  for (i=0; i<N;++i){
    c[i] = a[i] * b[i];
  }

  for (i=1; i<N; i=2*i+1){
    printf("%d^2 == %lf\n", i, c[i]);
  }

  return 0;
}
```

master.cpp

```
#include <cmath>
#include <unistd.h>
```

```
#include <fstream>
#include <iostream>
#include <sstream>
#include <sys/time.h>

#include "param.h"



Real U[NX][NY][NZ], V[NX][NY][NZ];
Real U_other[NX][NY][NZ], V_other[NX][NY][NZ];
int global_clock;


Real Uwx[T_MAX][2][SY][SZ], Uwy[T_MAX][SX][2][SZ], Uwz[T_MAX][SX][SY][2];
Real Vwx[T_MAX][2][SY][SZ], Vwy[T_MAX][SX][2][SZ], Vwz[T_MAX][SX][SY][2];

Real sU0[SX][SY][SZ], sV0[SX][SY][SZ];


extern "C" {
  void run_benchmark();
}

double wctime() {
  struct timeval tv;
  gettimeofday(&tv,NULL);
  return (double)tv.tv_sec + (double)tv.tv_usec*1e-6;
}



void fill_initial_condition() {
  global_clock=0;
  for (int x=0;x<NX;++x) {
    for (int y=0;y<NY;++y) {
      for (int z=0;z<NZ;++z) {
        U[x][y][z] = 1;
        V[x][y][z] = 0;
      }
    }
  }
  int bx = std::max(NX/4,NX/2-8),  ex = std::min(3*NX/4+1,NX/2+8);
  int by = std::max(NY/4,NY/2-8),  ey = std::min(3*NY/4+1,NY/2+8);
  int bz = std::max(NZ/4,NZ/2-8),  ez = std::min(3*NZ/4+1,NZ/2+8);
  for (int x=bx;x<ex;++x){
    for (int y=by;y<ey;++y){
      for (int z=bz;z<ez;++z){
        U[x][y][z] = 0.5;
        V[x][y][z] = 0.25+0.1*sin(x+sqrt(y)+cos(z));
      }
    }
  }
}


inline Real periodic(Real ar[NX][NY][NZ],int x, int y, int z) {
  x = ((x+100*NX)%NX+NX)%NX;
  y = ((y+100*NY)%NY+NY)%NY;
  z = ((z+100*NZ)%NZ+NZ)%NZ;
  //x = (x+NX)%NX;
  //y = (y+NY)%NY;
  //z = (z+NZ)%NZ;
  return ar[x][y][z];
}


void naive_proceed() {
  ++global_clock;

  auto lap = [](Real ar[NX][NY][NZ],int x, int y, int z) {
    auto ret = periodic(ar, x-1, y, z) + periodic(ar, x+1, y, z)
    + periodic(ar, x, y-1, z) + periodic(ar, x, y+1, z)
    + periodic(ar, x, y, z-1) + periodic(ar, x, y, z+1)
    - 6*ar[x][y][z];
    return ret / dx / dx;
  };

  for (int x=0;x<NX;++x) {
    for (int y=0;y<NY;++y) {
      for (int z=0;z<NZ;++z) {
        auto u = U[x][y][z],  v = V[x][y][z];
        auto du_dt = -Fe * u*v*v + Fu*(1-u) + Du * lap(U,x,y,z);
        auto dv_dt =  Fe * u*v*v - Fv*v     + Dv * lap(V,x,y,z);
        U_other[x][y][z] = U[x][y][z] + dt*du_dt;
        V_other[x][y][z] = V[x][y][z] + dt*dv_dt;
      }
    }
  }

  for (int x=0;x<NX;++x) {
    for (int y=0;y<NY;++y) {
      for (int z=0;z<NZ;++z) {
        U[x][y][z]=U_other[x][y][z];
      }
    }
  }
  for (int x=0;x<NX;++x) {
    for (int y=0;y<NY;++y) {
      for (int z=0;z<NZ;++z) {
        V[x][y][z]=V_other[x][y][z];
      }
    }
  }
```

```
}

void get_solution_at(int t, int x, int y, int z, Real &u, Real &v) {
  if(global_clock > t) fill_initial_condition();
  while(global_clock < t) naive_proceed();
  u = periodic(U,x,y,z);
  v = periodic(V,x,y,z);
}

int main () {

  fill_initial_condition();
  for(int x=0;x<SX;++x) {
    for(int y=0;y<SY;++y) {
      for(int z=0;z<SZ;++z) {
        double u,v; get_solution_at(0,x,y,z, u,v);
        sU0[x][y][z]=u;
        sV0[x][y][z]=v;
      }
    }
  }

  std::cerr << "Setting up wall values..." << std::endl;
  for(int t = 0;t<T_MAX;++t){
    for(int x=SX-2;x<SX;++x) {
      for(int y=0;y<SY;++y) {
        for(int z=0;z<SZ;++z) {
          double u,v; get_solution_at(t,x+t,y+t,z+t, u,v);
          Uwx[t][x-(SX-2)][y][z] = u;
          Vwx[t][x-(SX-2)][y][z] = v;
        }
      }
    }

    for(int x=0;x<SX;++x) {
      for(int y=SY-2;y<SY;++y) {
        for(int z=0;z<SZ;++z) {
          double u,v; get_solution_at(t,x+t,y+t,z+t, u,v);
          Uwy[t][x][y-(SY-2)][z] = u;
          Vwy[t][x][y-(SY-2)][z] = v;
        }
      }
    }

    for(int x=0;x<SX;++x) {
      for(int y=0;y<SY;++y) {
        for(int z=SZ-2;z<SZ;++z) {
          double u,v; get_solution_at(t,x+t,y+t,z+t, u,v);
          Uwz[t][x][y][z-(SZ-2)] = u;
          Vwz[t][x][y][z-(SZ-2)] = v;
        }
      }
    }
  }


  for(int trial=0;trial<10;++trial) {

    double time_begin = wctime();

    run_benchmark();

    double time_end = wctime();

    double flop = 29.0 * (SX-2)*(SY-2)*(SZ-2) *T_MAX;
    double time_elapse = time_end-time_begin;

    {
      const int t = T_MAX;
      double num=0,den=0;
      for(int x=0;x<SX-2;++x) {
        for(int y=0;y<SY-2;++y) {
          for(int z=0;z<SZ-2;++z) {
            double u,v; get_solution_at(t,x+t,y+t,z+t, u,v);
            num += std::abs(u-sU0[x][y][z]);
            den += 1;
          }
        }
      }
      std::ostringstream msg;
      msg << SX << " " << SY << " " << SZ << " " << T_MAX << " "
          << " t: " << time_elapse << " GFlops: " << flop/time_elapse/1e9<< " error: " << (num/den)
      std::ofstream log_file("benchmark.txt", std::ios::app);
      std::cout << msg.str() << std::endl;
      log_file << msg.str() << std::endl;
    }
  }
}
```

slave.c

```
#include <stdio.h>
#include "param.h"

extern Real sU0[SX][SY][SZ], sV0[SX][SY][SZ];
extern Real Uwx[T_MAX][2][SY][SZ], Uwy[T_MAX][SX][2][SZ], Uwz[T_MAX][SX][SY][2];
extern Real Vwx[T_MAX][2][SY][SZ], Vwy[T_MAX][SX][2][SZ], Vwz[T_MAX][SX][SY][2];



// double-buffered simulation state
Real sU[SX][SY][SZ], sV[SX][SY][SZ];
Real sU_1[SX][SY][SZ], sV_1[SX][SY][SZ];
```

```
void run_benchmark(){

  printf("Carrying out simulation...\n");

  // set initial condition
  for(int x=0;x<SX;++x) {
    for(int y=0;y<SY;++y) {
      for(int z=0;z<SZ;++z) {
        sU[x][y][z]=sU0[x][y][z];
        sV[x][y][z]=sV0[x][y][z];
      }
    }
  }

  for(int t = 0; t < T_MAX; ++t){
    // load communication values
    for(int x=SX-2;x<SX;++x) {
      for(int y=0;y<SY;++y) {
        for(int z=0;z<SZ;++z) {
          sU[x][y][z] = Uwx[t][x-(SX-2)][y][z];
          sV[x][y][z] = Vwx[t][x-(SX-2)][y][z];
        }
      }
    }

    for(int x=0;x<SX-2;++x) {
      for(int y=SY-2;y<SY;++y) {
        for(int z=0;z<SZ;++z) {
          sU[x][y][z] = Uwy[t][x][y-(SY-2)][z];
          sV[x][y][z] = Vwy[t][x][y-(SY-2)][z];
        }
      }
    }

    for(int x=0;x<SX-2;++x) {
      for(int y=0;y<SY-2;++y) {
        for(int z=SZ-2;z<SZ;++z) {
          sU[x][y][z] = Uwz[t][x][y][z-(SZ-2)];
          sV[x][y][z] = Vwz[t][x][y][z-(SZ-2)];
        }
      }
    }



    // destructively update the state
#define lap(ar, x, y, z)                        \
    ( ar[x][y+1][z+1] + ar[x+2][y+1][z+1]       \
      + ar[x+1][y][z+1] + ar[x+1][y+2][z+1]     \
      + ar[x+1][y+1][z] + ar[x+1][y+1][z+2]     \
        - 6*ar[x+1][y+1][z+1]) / dx / dx
    for(int x=0;x<SX-2;++x) {
      for(int y=0;y<SY-2;++y) {
        for(int z=0;z<SZ-2;++z) {
          Real u=sU[x+1][y+1][z+1] ;
          Real v=sV[x+1][y+1][z+1] ;

          Real du_dt = -Fe * u*v*v + Fu*(1-u) + Du * lap(sU,x,y,z);
          Real dv_dt =  Fe * u*v*v - Fv*v     + Dv * lap(sV,x,y,z);
          sU_1[x][y][z] = u+dt*du_dt;
          sV_1[x][y][z] = v+dt*dv_dt;
        }
      }
    }


    for(int x=0;x<SX-2;++x) {
      for(int y=0;y<SY-2;++y) {
        for(int z=0;z<SZ-2;++z) {
          sU[x][y][z] = sU_1[x][y][z];
          sV[x][y][z] = sV_1[x][y][z];
        }
      }
    }
  }

  // return the final condition
  for(int x=0;x<SX;++x) {
    for(int y=0;y<SY;++y) {
      for(int z=0;z<SZ;++z) {
        sU0[x][y][z]=sU[x][y][z];
        sV0[x][y][z]=sV[x][y][z];
      }
    }
  }

}
```

run.sh

```
cd /home/export/base/nsccwuxi_riken/riken/online1/sandbox/nushio_box/sunway-test/01-master/src/
make && make run
```

2.2.4 Results

Got the following results:

```
TODO
```

2.2.5 Discussion

理論的に実現可能な性能の性能の TODO%の性能を得た。