6.189 IAP 2007

Lecture 9

Debugging Parallel Programs

Debugging Parallel Programs is Hard-er

- Parallel programs are subject to the usual bugs
- Plus: new timing and synchronization errors
- And: parallel bugs often disappear when you add code to try to identify the bug

Visual Debugging of Parallel Programs

- A global view of the multiprocessor architecture
  - Processors and communication links
- See which communication links are used
  - Perhaps even change the data in transmission
- Utilization of each processor
  - Can identify blocked processors, deadlock

- “step” through functionality?
  - Lack of a global clock

- Likely won’t help with data races

TotalView

Debugging Parallel Programs

- Commercial debuggers
  - TotalView, …
- The **`printf`** approach
- gdb, MPI gdb, ppu/spu gdb, …
- Research debuggers
  - StreamIt Debugger, …

StreamIt Debugger

Cell Debugger in Eclipse IDE

Pattern-based Approach to Debugging

- "Defect Patterns": common kinds of bugs in parallel programs
  - Useful tips to prevent them
  - Recipes for effective resolution
- Inspired by empirical studies at University of Maryland
  - http://fc-md.umd.edu/softwareday//presentations/Session0/Keynote.pdf
- At the end of this course, will try to identify some common Cell defect patterns based on your feedback and projects

Defect Pattern: Erroneous Use of Language Features

- Examples
  - Inconsistent parameter types for get/send and put/receive
  - Required function calls
  - Inappropriate choice of functions
- Symptoms
  - Compile-type error (easy to fix)
  - Some defects may surface only under specific conditions
    - Number of processors, value of input, alignment issues
- Cause
  - Lack of experience with the syntax and semantics of new language features
- Prevention
  - Check unfamiliar language features carefully

Does Cell have too many functions?

- Yes! But you may not need all of them
- Understand a few basic features

```
spe_create_thread
spe_wait

spe_write_in_mbox
spe_stat_in_mbox

spe_read_out_mbox
spe_stat_out_mbox

spe_write_signal

spe_get_ls
spe_get_ps_area

spe_mfc_get
spe_mfc_put
spe_mfc_read_tag_status

spe_create_group
spe_get_event
```

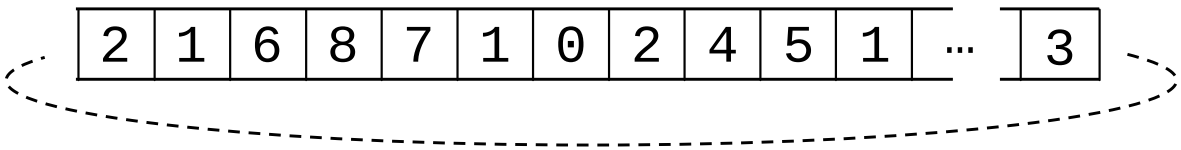
```
mfc_get
mfc_put
mfc_stat_cmd_queue
mfc_write_tag_mask
mfc_read_tag_status_all/any/immediate

spu_read_in_mbox
spu_stat_in_mbox

spu_write_out_mbox, spu_write_out_intr_mbox
spu_stat_out_mbox, spu_stat_out_intr_mbox

spu_read_signal1/2
spu_stat_signal1/2

spu_write_event_mask
spu_read_event_status
spu_stat_event_status
spu_write_event_ack

spu_read_decrementer
spu_write_decrementer
```

Defect Pattern: Space Decomposition

- Incorrect mapping between the problem space and the program memory space
- Symptoms
  - Segmentation fault (if array index is out of range)
  - Incorrect or slightly incorrect output
- Cause
  - Mapping in parallel version can be different from that in serial version
    - Array origin is different in every processor
    - Additional memory space for communication can complicate the mapping logic
- Prevention
  - Validate memory allocation carefully when parallelizing code

Example Problem

A sequence of *N* cells



- N cells, each of which holds an integer [0..9]
  - **`cell[0]=2, cell[1]=1, …, cell[N-1]=3`**
- In each step, cells are updated using values of neighboring cells
  - **`cellnext[x] = (cell[x-1] + cell[x+1]) mod 10`**
  - **`cellnext[0]=(3+1), cellnext[1]=(2+6), …`**
  - Assume the last cell is connected to the first cell
- Repeat for *steps* times

Sequential Implementation

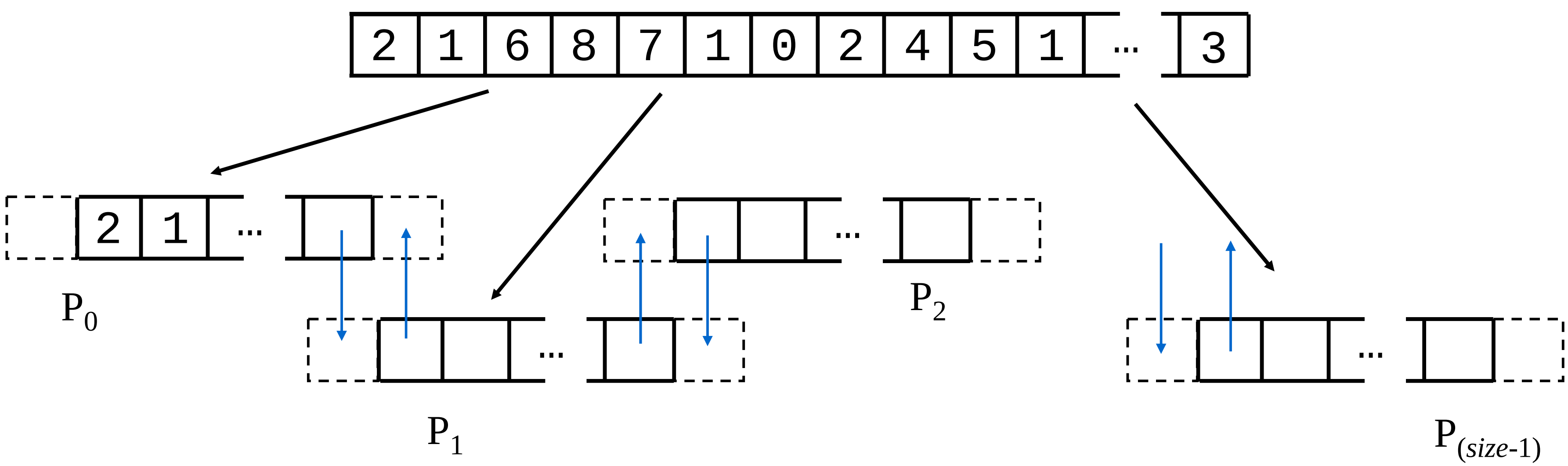
- Approach to implementation
  - Use an integer array **`buffer[]`** for current cell values
  - Use a second array **`nextbuffer[]`** to store the values for next step
  - Swap the buffers

Sequential C Code

```
/* Initialize cells */
int x, n, *tmp;
int *buffer     = (int*)malloc(N * sizeof(int));
int *nextbuffer = (int*)malloc(N * sizeof(int));
FILE *fp = fopen("input.dat", "r");
if (fp == NULL) { exit(-1); }
for (x = 0; x < N; x++) { fscanf(fp, "%d", &buffer[x]); }
fclose(fp);

/* Main loop */
for (n = 0; n < steps; n++) {
  for (x = 0; x < N; x++) {
    nextbuffer[x] = (buffer[(x-1+N)%N]+buffer[(x+1)%N]) % 10;
  }
  tmp = buffer; buffer = nextbuffer; nextbuffer = tmp;
}

/* Final output */
...
free(nextbuffer); free(buffer);
```

Approach to a Parallel Version

- Each processor keeps 1/size cells
  - size = number of processors

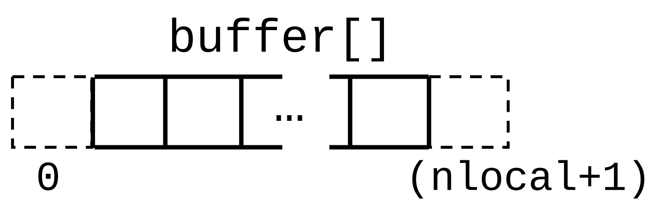


- Each processor needs to:
  - update the locally-stored cells
  - exchange boundary cell values between neighboring processes

Decomposition

Where are the bugs?

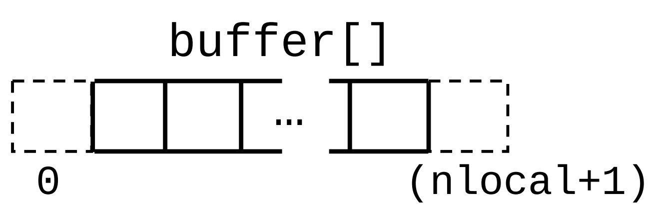
```
nlocal     = N / size;
buffer     = (int*)malloc((nlocal+2) * sizeof(int));
nextbuffer = (int*)malloc((nlocal+2) * sizeof(int));

/* Main loop */
for (n = 0; n < steps; n++) {
  for (x = 0; x < nlocal; x++) {
    nextbuffer[x] = (buffer[(x-1+N)%N]+buffer[(x+1)%N]) % 10;
  }
  /* Exchange boundary cells with neighbors */
  ...

  tmp = buffer; buffer = nextbuffer; nextbuffer = tmp;
}
```



Decomposition

Where are the bugs?

```
nlocal     = N / size;      N may not be divisible by size
buffer     = (int*)malloc((nlocal+2) * sizeof(int));
nextbuffer = (int*)malloc((nlocal+2) * sizeof(int));

/* Main loop */
for (n = 0; n < steps; n++) {
  for (x = 0; x < nlocal; x++) {  (x = 1; x < nlocal+1; x++)
    nextbuffer[x] = (buffer[(x-1+N)%N]+buffer[(x+1)%N]) % 10;
  }
  /* Exchange boundary cells with neighbors */
  ...

  tmp = buffer; buffer = nextbuffer; nextbuffer = tmp;
}
```



Defect Pattern: Synchronization

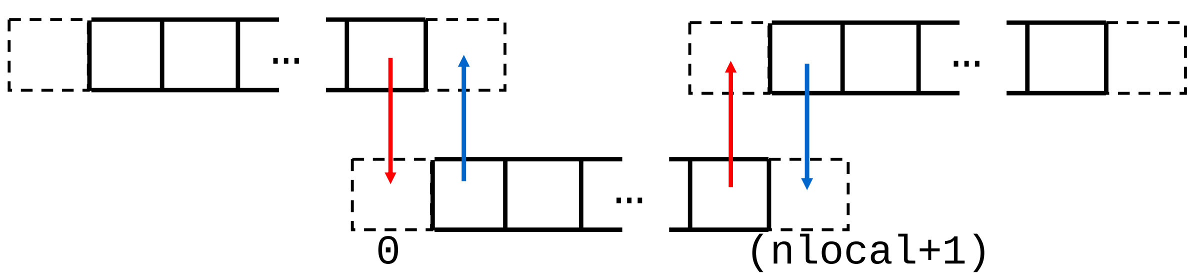
- Improper coordination between processes
  - Well-known defect type in parallel programming
  - Deadlocks, race conditions
- Symptoms
  - Program hangs
  - Incorrect/non-deterministic output
- Causes
  - Some defects can be very subtle
  - Use of asynchronous (non-blocking) communication can lead to more synchronization defects
- Preventions
  - Make sure that all communication is correctly coordinated

Communication

Where are the bugs?

```
/* Main loop */
for (n = 0; n < steps; n++) {
  for (x = 1; x < nlocal+1; x++) {
    nextbuffer[x] = (buffer[(x-1+N)%N]+buffer[(x+1)%N]) % 10;
  }
  /* Exchange boundary cells with neighbors */
  receive (&nextbuffer[0],        (rank+size-1)%size);
  send    (&nextbuffer[nlocal],   (rank+1)%size);
  receive (&nextbuffer[nlocal+1], (rank+1)%size);
  send    (&nextbuffer[1],        (rank+size-1)%size);
  tmp = buffer; buffer = nextbuffer; nextbuffer = tmp;
}
```

- Deadlock



Modes of Communication

- Recall there are different types of sends and receives
  - Synchronous
  - Asynchronous
  - Blocking
  - Non-blocking

- Tips for orchestrating communication
  - Alternate the order of sends and receives
  - Use asynchronous and non-blocking messages where possible

Defect Pattern: Side-effect of Parallelization

- Ordinary serial constructs may have unexpected side-effects when they used concurrently
- Symptoms
  - Various correctness and performance problems
- Causes
  - Sequential part of code is overlooked
  - Typical parallel programs contain only a few parallel primitives, and the rest of the code is a sequential program running many times
- Prevention
  - Don't just focus on the parallel code
  - Check that the serial code is working on one processor, but remember that the defect may surface only in a parallel context

Data I/O in SPMD Program

Where are the bugs?

```
/* Initialize cells with input file */
fp = fopen("input.dat", "r");
if (fp == NULL) { exit(-1); }
nskip = ...
for (x = 0; x < nskip; x++) { fscanf(fp, "%d", &dummy);}
for (x = 0; x < nlocal; x++) { fscanf(fp, "%d", &buffer[x+1]);}
fclose(fp);

/* Main loop */
...
```

Data I/O in SPMD Program

Where are the bugs?

```
/* Initialize cells with input file */
fp = fopen("input.dat", "r");
if (fp == NULL) { exit(-1); }
nskip = ...
for (x = 0; x < nskip; x++) { fscanf(fp, "%d", &dummy);}
for (x = 0; x < nlocal; x++) { fscanf(fp, "%d", &buffer[x+1]);}
fclose(fp);

/* Main loop */
...
```

- File system may cause performance bottleneck if all processors access the same file simultaneously
- Schedule I/O carefully

Data I/O in SPMD Program

Where are the bugs?

```
/* Initialize cells with input file */
if (rank == MASTER) {
fp = fopen("input.dat", "r");
if (fp == NULL) { exit(-1); }
for (x = 0; x < nlocal; x++) { fscanf(fp, "%d", &buffer[x+1]);}
for (p = 1; p < size; p++) {
  /* Read initial data for process p and send it */
}
fclose(fp);
}
else {
  /* Receive initial data*/
}
```

- Often only one processor (master) needs to do the I/O

Generating Initial Data

Where are the bugs?

```
/* What if we initialize cells with random values... */
srand(time(NULL));
for (x = 0; x < nlocal; x++) {
  buffer[x+1] = rand() % 10;
}

/* Main loop */
...
```

Generating Initial Data

Where are the bugs?

```
/* What if we initialize cells with random values... */
~~srand(time(NULL));~~    srand(time(NULL) + rank);
for (x = 0; x < nlocal; x++) {
  buffer[x+1] = rand() % 10;
}

/* Main loop */
...
```

- All processors might use the same pseudo-random seed (and hence sequence), spoiling independence
- Hidden serialization in rand() causes performance bottleneck

Defect Pattern: Performance Scalability

- Symptoms
  - Sub-linear scalability
  - Performance much less than expected
  - Most time spent waiting
- Causes
  - Unbalanced amount of computation
  - Load balancing may depend on input data
- Prevention
  - Make sure all processors are “working” in parallel
  - Profiling tools might help

Summary

- Some common bugs in parallel programming
  - Erroneous use of language features
  - Space decomposition
  - Side-effect of parallelization
  - Synchronization
  - Performance scalability
- There are other kinds of bugs as well: data race

Comment on Data Race Detection

- Trace analysis can help
  - Execute program
  - Generate trace of all memory accesses and synchronization operations
  - Build a graph of orderings (solid arrows below) and conflicting memory references (dashed lines below)
  - Detect races (when two nodes connected by dashed lines are not ordered by solid arrows)
- Intel Thread Checker is an example
  - More tools available for automatic race detection

Trend in Debugging Technology

- Trace-based
- Checkpointing
- Replay

- One day… you'll have the equivalent of TiVo for debugging your programs