Part IV: Programming Strategies

Goal: Introduce scalable algorithms and strategies for developing scalable solutions

Red Blue Discussion

- Regarding the Red/Blue computation
  - How did you allocate the array? Why?
  - How was the work assigned?
  - How do the threads communicate?

Data and Task Parallelism

- Many definitions … parallelize the data or work?
- In a data parallel computation the parallelism is applied by performing the same (or similar) operations to different items of data at the same time; the parallelism grows with the size of the data
- In a task parallel computation the parallelism is applied by performing distinct computations -- or tasks -- at the same time; with the number of tasks fixed, the parallelism is not scalable

Contrast solutions to preparing a banquet

Peril-*L* …

- A pseudo-language to assist in discussing algorithms and languages
- Don't panic--the name is just a joke
- Goals:
  - Be a minimal notation to describe parallelism
  - Be universal, unbiased towards languages or machines
  - Allow reasoning about performance (using the CTA)

I'm interested how well this works

Base Language is C

- Peril-*L* uses C as its notation for scalar computation, but any scalar language is OK
- Advantages
  - Well known and familiar
  - Capable of standard operations & bit twiddling
- Disadvantages
  - Low level
  - No goodies like OO

This is not the way to design a || language

Threads

- The basic form of parallelism is a thread
- Threads are specified by

```
forall
    <int var> in ( <index range spec> ) {<body> }
```

- Semantics: spawn *k* threads running *body*

```
forall thID in (1..12) {
  printf("Hello, World, from thread %i\n", thID);
}
```

<*index range spec*> is any reasonable (ordered) naming

Thread Model is Asynchronous

- Threads execute at their own rate
- The execution relationships among threads are not known or predictable
- To cause threads to synchronize, we have

```
barrier;
```

- Threads arriving at barriers suspend execution until all threads in its `forall` arrive there; then they're all released
- Reference to the `forall` index identifies the thread

Memory Model

- Two kinds of memory: local and global
  - All variables declared in a thread are local
  - Any variable w/ <u>underlined_name</u> is global
- Names (usually indexed) work as usual
  - Local variables use local indexing
  - Global variables use global indexing
- Memory is based on CTA, so performance:
  - Local memory references are unit time
  - Global memory references take λ time

Notice that the default vars are local vars

Memory Read Write Semantics

- Local Memory behaves like the RAM model
- Global memory
  - Reads are concurrent, so multiple processors can read a memory location at the same time
  - Writes must be exclusive, so only one processor can write a location at a time; the possibility of multiple processors writing to a location is not checked and if it happens the result is unpredictable

In PRAM terminology, this is CREW, but it's not a PRAM

Example: Try 1

- Shared memory programs are expressible
- The first (erroneous) Count 3s program is

```
int *array, length, count, t;
  ... initalize globals here ...
forall thID in (0..t-1) {
   int i, length_per=length/t;
   int start=thID*length_per;
   for (i=start; i<start+length_per; i++) {
    if (array[i] == 3)
      count++;
    }
}
```

- Variable usage is now obvious

Why Is This Not Shared Memory?

- Peril-*L* is not a shared memory model because:
  - It distinguishes between local and global memory costs … that's why it's called "global"
- Peril-*L* is not a PRAM because
  - It is founded on the CTA
  - By distinguishing between local and global memory, it distinguishes their costs
  - It is asynchronous

These may seem subtle but they matter

Getting Global Writes Serialized

- To insure the exclusive write Peril-*L* has

```
exclusive { <body> }
```

- The semantics are that a thread can execute <*body*> only if no other thread is doing so; if some thread is executing, then it must wait for access; sequencing through `exclusive` may not be fair

Exclusive gives behavior, not mechanism

Example: Try 4

- The final (correct) Count 3s program

```
int *array, length, count, t;
forall thID in (0..t-1) {
  int i, priv_count=0; len_per_th=length/t;
  int start=thID * len_per_th;
  for (i=start; i<start+len_per_th; i++) {
    if (array[i] == 3)
      priv_count++;
  }
  exclusive {count += priv_count; }
}
```

Padding is irrelevant … it's implementation

Full/Empty Memory

- Memory usually works like information:
  - Reading is repeatable w/o "emptying" location
  - Writing is repeatable w/o "filling up" location
- Matter works differently
  - Taking something from location leaves vacuum
  - Placing something requires the location be empty
- Full/Empty: Applies matter idea to memory

  … F/E variables help serializing

Use the `apostrophe’` suffix to identify F/E

Treating memory as matter

- A location can be read only if it's filled
- A location can be written only it's empty

Location contents	Variable Read	Variable Write
Empty	Stall	Fill w/value
Full	Empty of value	Stall

- Scheduling stalled threads may not be fair

We'll find uses for this next week

Reduce and Scan

- Aggregate operations use APL syntax
  - Reduce: <*op*>/<*operand*> for <*op*> in {+, *, &&, ||, max, min}; as in `+/priv_sum`
  - Scan: <*op*>\<*operand*> for <*op*> in {+, *, &&, ||, max, min}; as in `+\local_finds`
- To be portable, use reduce & scan rather than programming them

```
exclusive {count += priv_count; }     "WRONG"
count = +/priv_count;                 "RIGHT"
```

Reduce/Scan Imply Synchronization

Reduce/Scan and Memory

- When reduce/scan involve local memory

```
priv_count= +/priv_count;
```

  - The local is assigned the global sum
  - This is an implied broadcast

```
priv_count= +\priv_count;
```

  - The local is assigned the prefix sum to that pt
  - No implied broadcast
- Assigning a reduce/scan value to a local forces a barrier, but assigning reduce value to a global does not

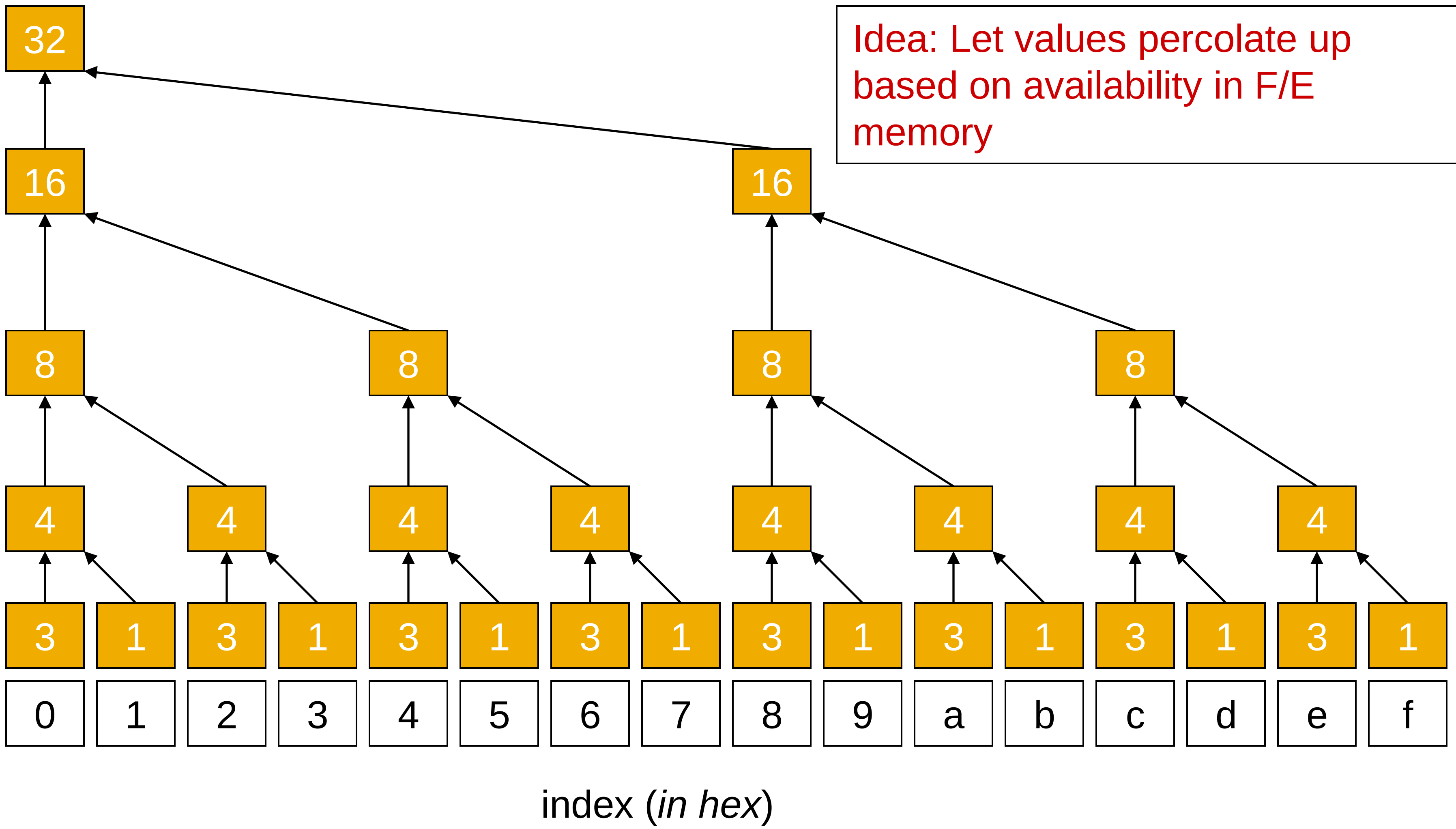
Peril-*L* Summary

- Peril-*L* is a pseudo-language
- No implementation is implied, though performance is
- Discuss: How efficiently could Peril-*L* run on previously discussed architectures?
  - CMP, SMPbus, SMPx-bar, Cluster, BlueGeneL
  - Features: C, Threads, Memory (G/L/f/e), */*, \

Using Peril-*L*

- The point of a pseudocode is to allow detailed discussion of subtle programming points without being buried by the extraneous detail
- To illustrate, consider some parallel computations …
  - Tree accumulate
  - Balanced parens

Slick Tree Accumulate Using F/E



Idea: Let values percolate up based on availability in F/E memory

Naïve F/E Tree Accumulation

```
int nodeval'[P];                              Global full/empty vars to save right child val
forall ( index in (0..P-1) ) {
 int val2accum; int stride = 1;               val2accum: locally computed val
 nodeval'[index] = val2accum;                 Assign initially to tree node
 while (stride < P) {                         Begin logic for tree
  if (index % (2*stride) == 0) {
   nodeval'[index]=nodeval'[index]+nodeval'[index+stride];
   stride = 2*stride;
  }
  else {
   break;   Exit, if not now a parent
  }
 }
}
```

Caution: This implementation is wrong …

Naïve F/E Tree Accumulation

```
int nodeval'[P];
forall ( index in (0..P-1) ) {
 int val2accum; int stride = 1;
 nodeval'[index] = val2accum;
 while (stride < P) {
  if (index % (2*stride) == 0) {
   nodeval'[index]=nodeval'[index]+nodeval'[index+stride];
   stride = 2*stride;
  }
  else {
   break;
  }
 }
}
```

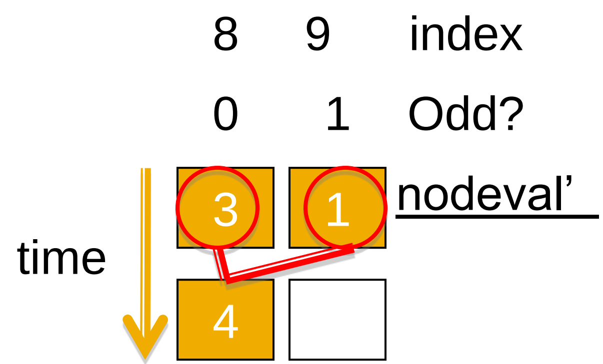
Global full/empty vars to save right child val

`val2accum`: *locally computed val*

Assign initially to tree node

Begin logic for tree

Exit, if not now a parent



Caution: This implementation is wrong …

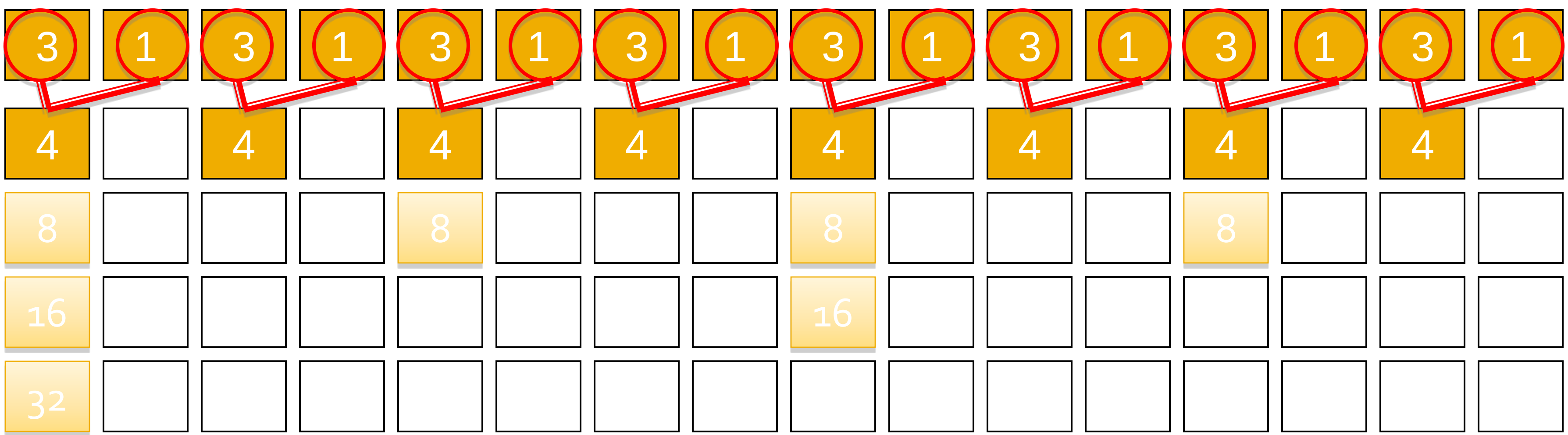
Round 1 of Tree Accum …

0 1 2 3 4 5 6 7 8 9 a b c d e f

index (*in hex*)

0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1

index % (2 * stride)



nodeval[index]

Caution: This implementation is wrong …

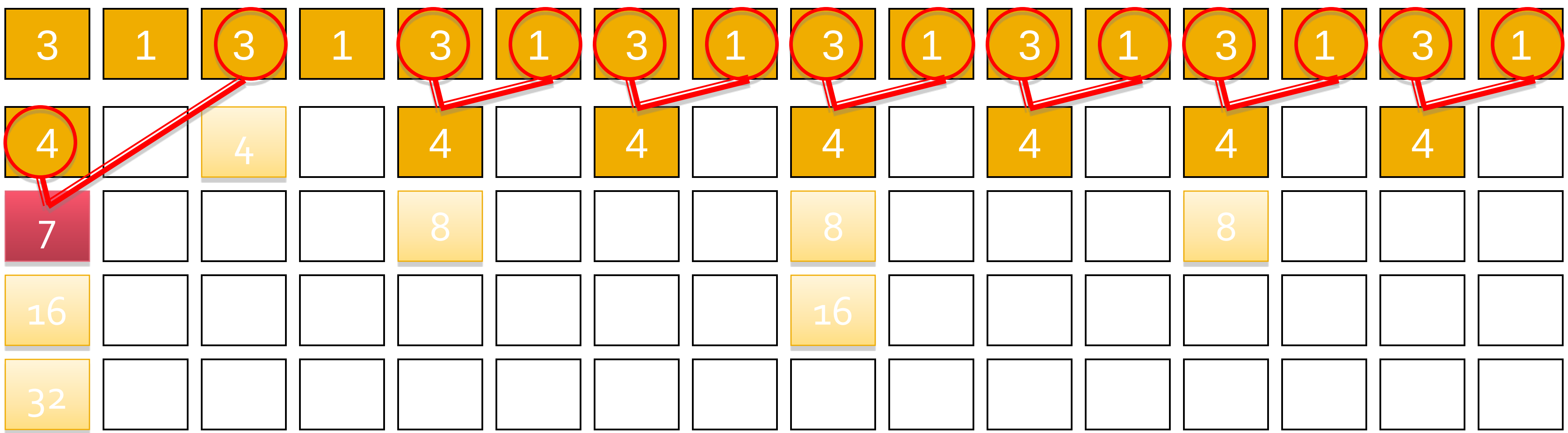
But What If P_2 is Slow, P_0 Fast?

0 1 2 3 4 5 6 7 8 9 a b c d e f

index (*in hex*)

0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1

index % (2 * stride)



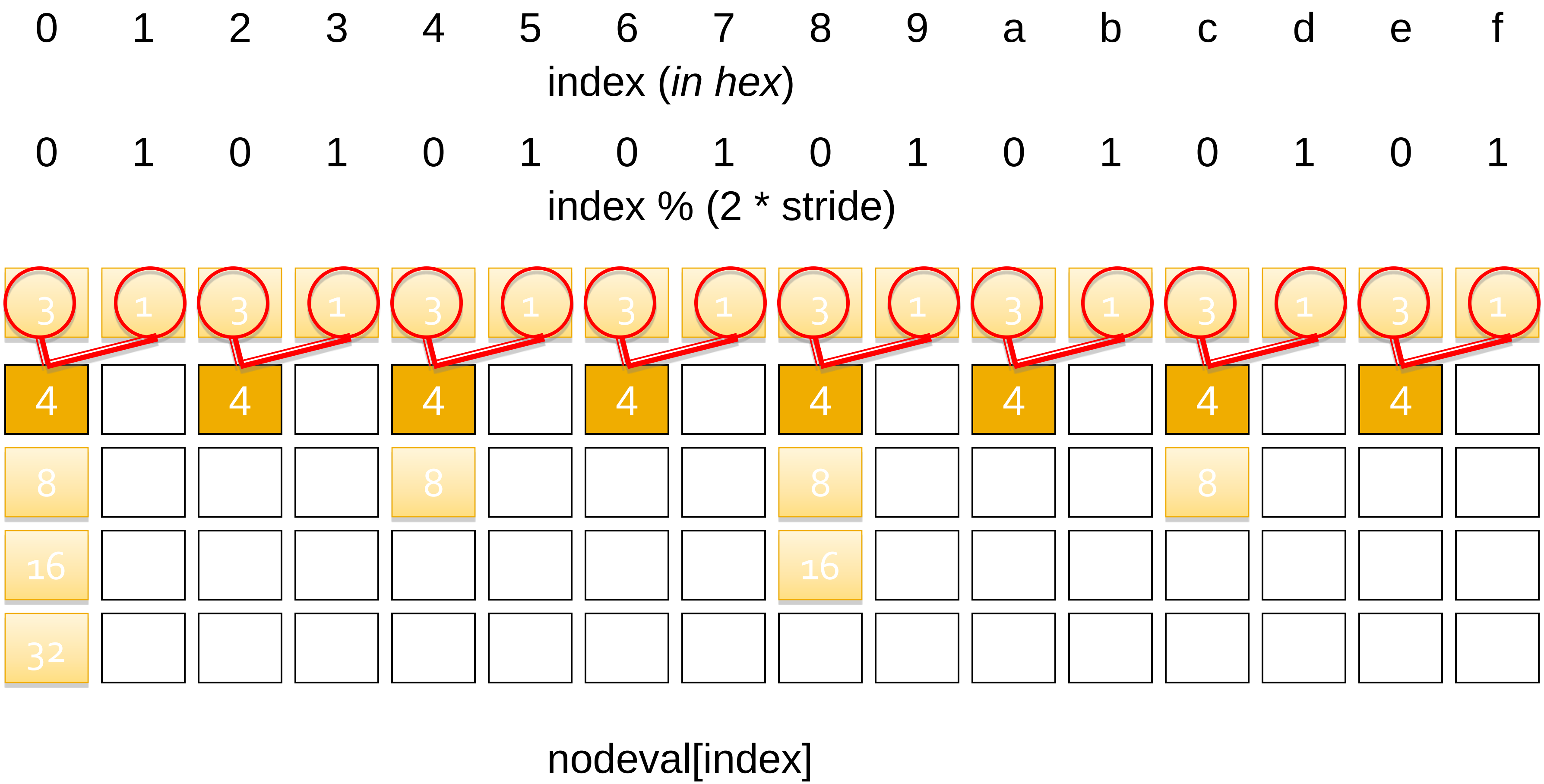
nodeval[index]

Caution: This implementation is wrong …

Introduce Barrier to Synch Levels

```
int nodeval'[P];                          Global full/empty vars to save right child val
forall ( index in (0..P-1) ) {
 int val2accum; int stride = 1;        val2accum: locally computed val
 nodeval'[index] = val2accum;          Assign initially to tree node
 while (stride < P) {                  Begin logic for tree
  if (index % (2*stride) == 0) {
   nodeval'[index]=nodeval'[index]+nodeval'[index+stride];
   stride = 2*stride;
  }
  else {
   break;   Exit, if not now a parent
  }
 barrier;
 }
}
```

Barrier Stops Until Stable State



The Problem With Barriers

- In many places barriers are essential to the logic of a computation, but …
- In many cases they are just an implementational device to overcome (for example) false dependences
- Avoid them when possible
  - They force the ||-ism to drop to zero
  - Often costly even when all threads arrive at once

Asynchronous Tree Accumulate

```
int nodeval'[P];                                   Global full/empty vars to save right child val
forall ( index in (0..P-1) ) {
 int val2accum;   int stride = 1;
 while (stride < P) {                              Begin logic for tree
  if (index % (2*stride) == 0) {
   val2accum=val2accum+nodeval'[index+stride];
   stride = 2*stride;
  }
  else {
   nodeval'[index]=val2accum;                      Assign val to F/E memory
   break;                                          Exit, if not now a parent
  }
 }
}
```

The "full" Applies To Root Only

0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f

index (*in hex*)

0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

index % (2 * stride)

3	1	2	2	2	2	3	1	2	2	3	1	3	1	2	2
4		4		4		4		4		4		4		4	
8				8				8				8			
16								16							
32															

nodeval[index]

Critique of Tree Accumulate

- Both the synchronous and asynchronous accumulates are available to us, but we usually prefer the asynch solution
- Notice that the asynch solution uses data availability as its form of synchronization

Peril-L For ((xxx))

```
char *symb[n];
forall pID in (0..P-1) {
  int i, len_per_th=length/t;
  int start=pID * len_per_th;
  int o=0, c=0;
  for (i=start; i<start+len_per_th; i++) {
    if (symb[i] == "(" )
      o++;
    if (symb[i] == ")" ) {
      o--;
      if (o < 0) {
        c++; o = 0;
      }
    }
  }
```

Break

Thinking About Parallel Algorithms

- Computations need to be reconceptualized to be effective parallel computations
- Three cases to consider
  - Unlimited parallelism -- issue is grain
  - Fixed ||ism -- issue is performance
  - Scalable parallelism -- get all performance that is *realistic* and *build in flexibility*
- Consider the three as an exercise in
  - Learning Peril-*L*
  - Thinking in parallel and discussing choices

The Problem: Alphabetize

- Assume a linear sequence of records to be alphabetized
- Technically, this is parallel sorting, but the full discussion on sorting must wait
- Solutions
  - Unlimited: Odd/Even
  - Fixed: Local Alphabetize
  - Scalable: Batcher’s Sort

Unlimited Parallelism (O/E Sort, I)

```
bool continue = true;
rec L[n];
while (continue) do {
 forall (i in (1:n-2:2)){
 rec temp;
 if (strcmp(L[i].x,L[i+1].x)>0){
    temp   = L[i];
    L[i]   = L[i+1];
    L[i+1] = temp;
  }
 }
```

The data is global

Stride by 2

Is o/even pair misordered?

Yes,fix

Data is referenced globally

Unlimited Parallelism (O/E Sort, II)

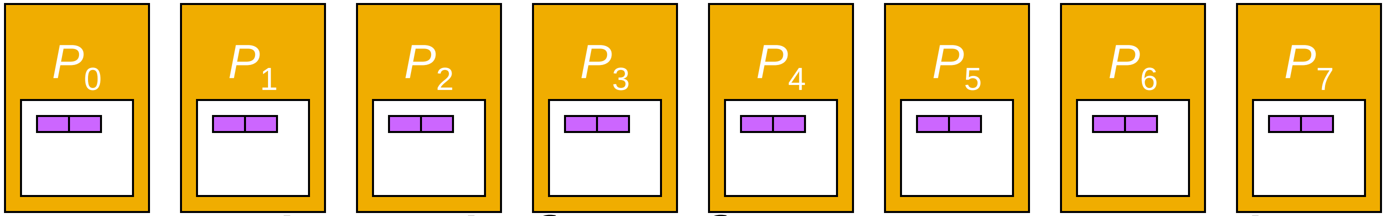
```
forall (i in (0:n-2:2))    {   Stride by 2
 rec temp;
 bool done = true;             Set up for termination test
 if (strcmp(L[i].x,L[i+1].x)>0){  Is e/odd pair misordered?
   temp   = L[i];              Yes, interchange
   L[i]   = L[i+1];
   L[i+1] = temp;
   done   = false;             Not done yet
 }
 continue= !(&&/ done);        Were any changes made?
}
}
```

Reflection on Unlimited Parallelism

- Is solution correct … are writes exclusive?
- What's the effect of process spawning overhead?
- How might this algorithm be executed for n=10,000, P=1000
- What is the performance?
- Are the properties of this solution clear from the Peril-*L* code?

1 More Problem w/Unlimited Model

- The criticism of fine-grain logical processes is they will usually be *emulated*; it's much slower than doing the work directly.
- Can we compile logical threads to tight code?
- Possibly, but consider this model



- Imagine data shifts left one item … what's the cost for 100,000 local values?

Generalizing "trivialized" operations is hard

Recall …

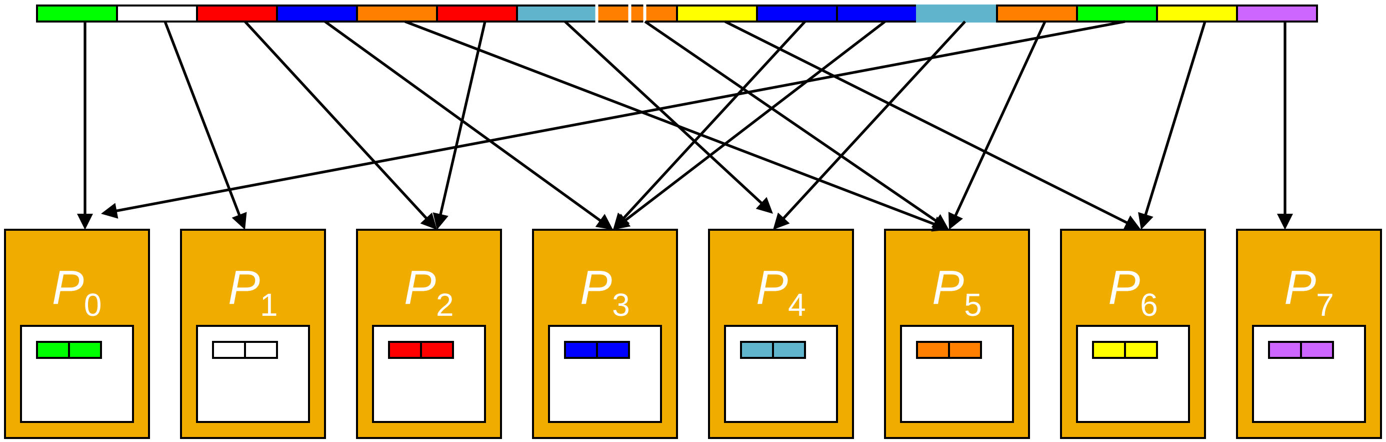
- We are illustrating the Peril-L notation for writing machine/language independent parallel programs
  - The "unlimited parallel solution" is O/E Sort
    - All data references were to global data
    - Threads spawned for each half step
    - Ineffective use of parallelism requiring threads to be created and implemented literally
  - Now consider a "fixed parallel solution"

Fixed Algorithm

- Postulate a process for handling each letter of the alphabet -- 26 Latin letters
- Logic
  - Processes scan records counting how many records start w/their letter handle
  - Allocate storage for those records, grab & sort
  - Scan to find how many records ahead precede

Cartoon of Fixed Solution

- Move locally



- Sort
- Return

Fixed Part 1: Introduce 2 functions

```
rec L[n];                                      The data is global
forall (index in (0..25)) {                    A thread for each letter
 int myAllo = mySize(L, 0);                    Number of local items
 rec LocL[] = localize(L[]);                   Make data locally ref-able
 int counts[26] = 0;                           Count # of each letter
 int i, j, startPt, myLet;
 for (i=0; i<myAllo; i++)  {                   Count number w/each letter
   counts[letRank(charAt(LocL[i].x,0))]++;
 }
 counts[index] = +/ counts[index];             Figure no. of each letter
 myLet = counts[index];                        Number of records of my letter
 rec Temp[myLet];                              Alloc local mem for records
```

Fixed Part 2

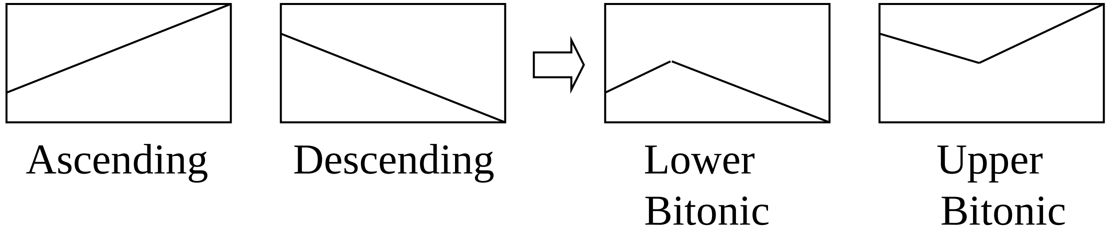
```
j = 0;                                  Index for local array
for(i=0; i<n; i++) {                    Grab records for local αbetize
 if(index==letRank(charAt(L[i].x,0)))
   Temp[j++]= L[i];                     Save record locally
}
alphabetizeInPlace(Temp[]);             Alphabetize within this letter
startPt=+\myLet;                        Scan counts # records ahead
                                           of these; scan synchs, so
                                           OK to overwrite L, post-sort
j=startPt-myLet;                        Find my start index in global
for(i=0; i<count; i++){                 Return records to global mem
 L[j++]=Temp[i];
}
}
```

Reflection on Fixed ||ism

- Is solution correct … are writes exclusive?
- Is “moving the data twice” efficient?
- How might this algorithm be executed for n=10,000, P=1000
- What is the performance?
- Are the properties of this solution clear from the Peril-*L* code?

Scalable Sort

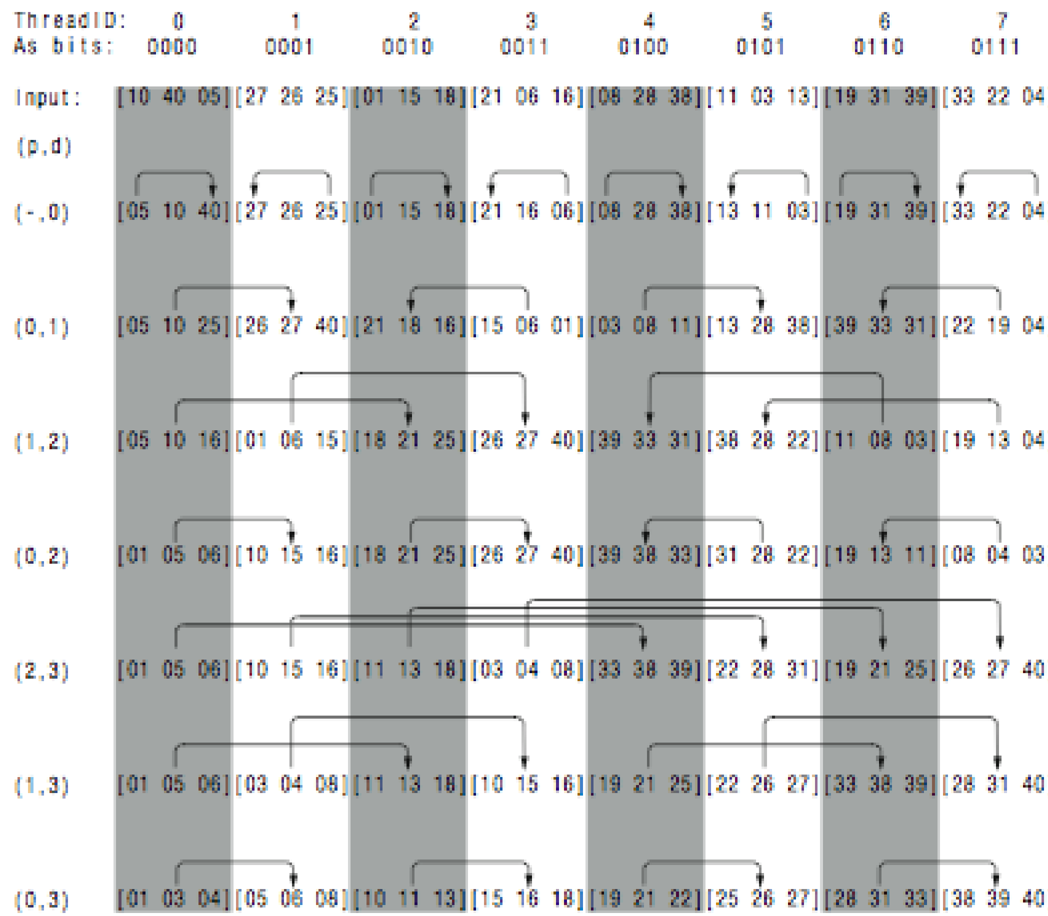
- Batcher's algorithm -- not absolute best, but illustrates a dramatic paradigm shift
- Bitonic Sort is based on a bitonic sequence:
- a sequence with increasing and decreasing subsequences



- Merging 2 sorted sequences makes bitonic

Batcher's Sort

- Skip recursive start; start w/ local sort
- Control by thread ID of paired processes
- (p,d) controls it: start at (-,0), d counts up, p down from d-1
- p = process pairs
- d = direction is d^{th} bit



Bitonic Sort, Closer Look

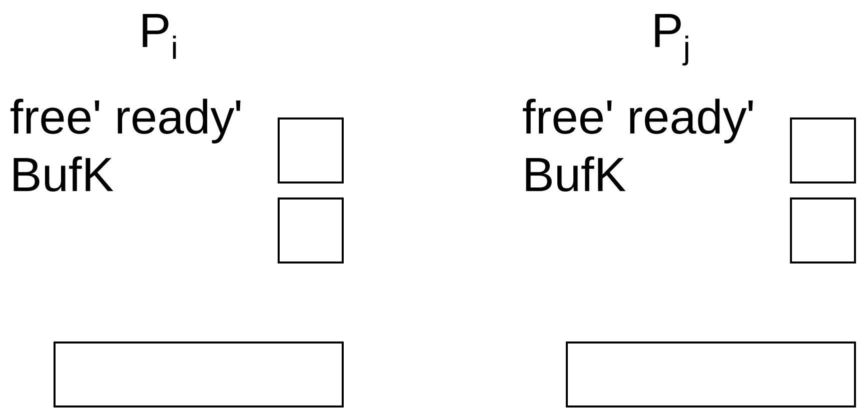
ThreadID:	0	1	2	3	4	5	6	7
As bits:	0000	0001	0010	0011	0100	0101	0110	0111
Input:	[10 40 05]	[27 26 25]	[01 15 18]	[21 06 16]	[08 28 38]	[11 03 13]	[19 31 39]	[33 22 04]
(p,d)								
(-,0)	[05 10 40]	[27 26 25]	[01 15 18]	[21 16 06]	[08 28 38]	[13 11 03]	[19 31 39]	[33 22 04]
(0,1)	[05 10 25]	[26 27 40]	[21 18 16]	[15 06 01]	[03 08 11]	[13 28 38]	[39 33 31]	[22 19 04]
(1,2)	[05 10 16]	[01 06 15]	[18 21 25]	[26 27 40]	[39 33 31]	[38 28 22]	[11 08 03]	[19 13 04]
(0,2)	[01 05 06]	[10 15 16]	[18 21 25]	[26 27 40]	[39 38 33]	[31 28 22]	[19 13 11]	[08 04 03]

Logic of Batcher's Sort

- Assumption: 2^x processes, ascending result
- Leave data in place globally, find position
  - Reference data locally, say *k* items
  - Create (key, input position) pairs & sort these
  - Processes are asynch, though alg is synchronous
  - Each process has a buffer of size *k* to exchange data -- write to neighbor's buffer
  - Use F/E var to know when to write (other buffer empty) and when to read (my buffer full)
  - Merge to keep (lo or hi) half data, and insure sorted
  - Go till control values end; use index to grab original rec

Data Transfer

- Use one buffer per processor plus to F/E variables: free' and ready'
  - free' is full when neighbor's buffer can be filled
  - ready' is empty until local buffer is filled



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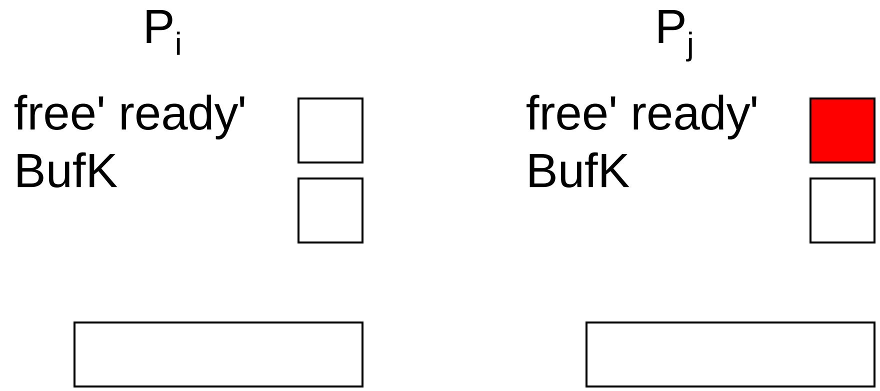

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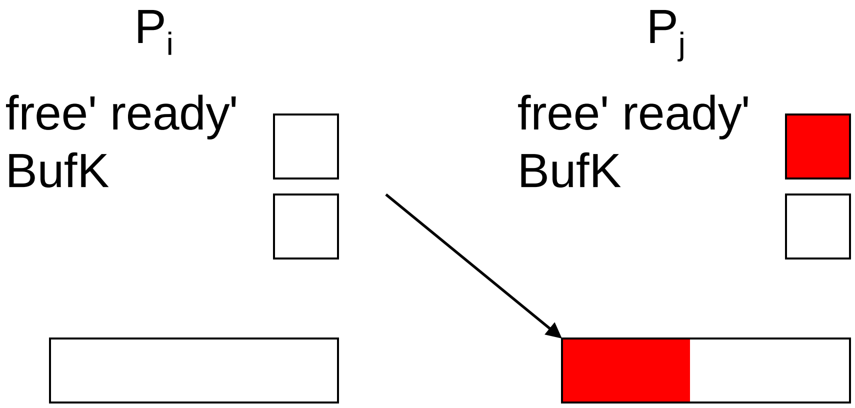

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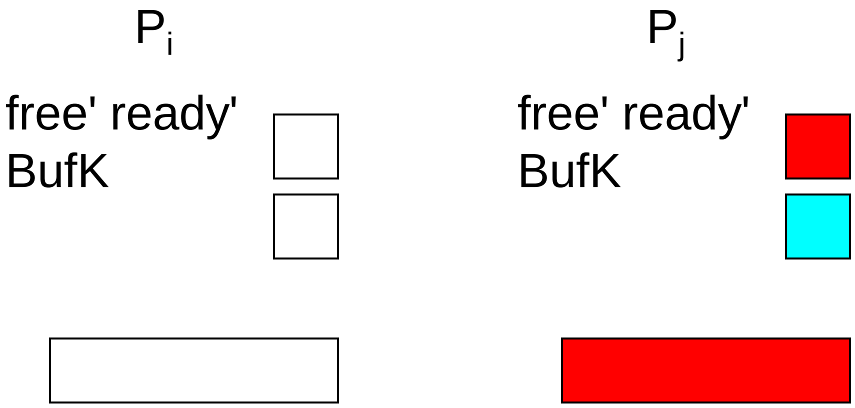

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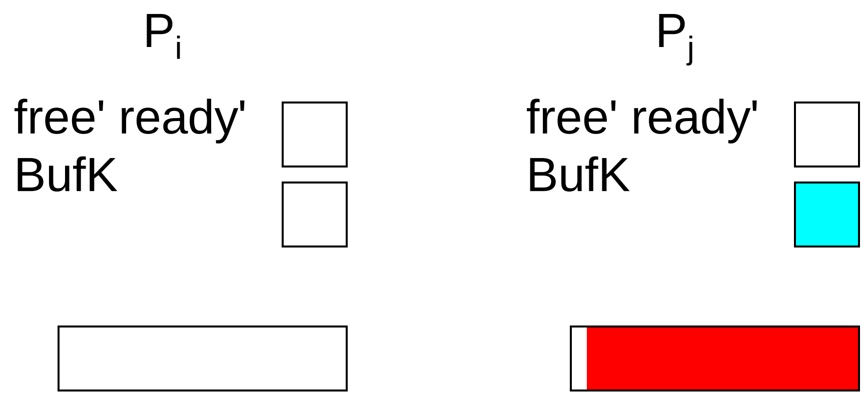


Details on Data Transfer

```
alphabetizeInPlace(K[],bit(index,0));   Local sort, up or down based on bit 0
for(d=1; d<=m; d++)  {                   Main loop, m phases
 for(p=d-1; p<0; p--)  {                 Define p for each sub-phase
   stall=free'[neigh(index,p)];          Stall till I can give data
   for(i=0; i<size; i++)  {              Send my data to neighbor
     BufK[neigh(index,p)][i]=K[i];
   }
   ready'[neigh(index,p)]=true;          Release neighbor to go
   stall=ready'[index];                  Stall till my data is ready
   … Merge two buffers, keeping half
  }
}
```

Bitonic Sort In Text

- Details are in the book …
- Discussion Question: What, if any, is the relationship between Bitonic Sort and Quick Sort?

- http://www.tools-of-computing.com/tc/CS/Sorts/bitonic_sort.htm

Sample Sort

- The idea of sending data to where it belongs is a good one … the Fixed Solution works out where that is, and Batcher's Sort uses a general scheme
- Can we figure this out with less work?
  - Estimate where the data goes by sampling
  - Send a random sampling of a small number (log n?) of values from each process to p_0
  - p_0 sorts the values and picks the P-1 "cut points", sends them back to all processors

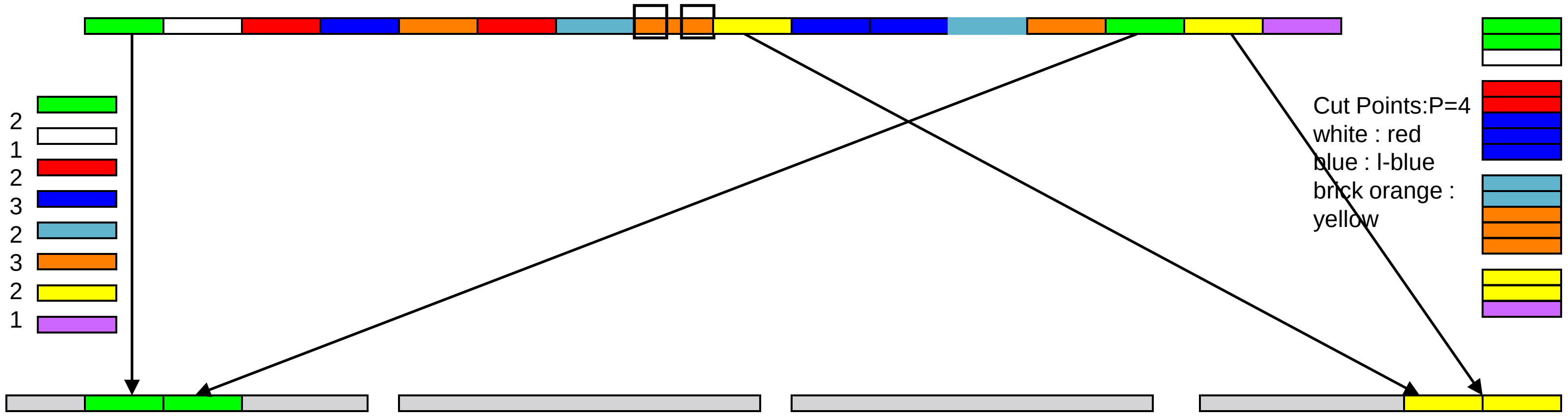
Sample size depends on the values of n and P

Sample Sort (Continued)

- After receiving the “cut points” each process…
  - Sends its values to the process responsible for each range
  - Each process sorts
  - A scan of the actual counts can place the “cut points” into the right processes
  - An adjustment phase “scooches” the values into final position

Cartoon of Sample Sort Solution

- Sample v values from all processors to p_0
- p_0 sorts and figures P-1 cutpoints
- Move them there



- Adjust position

Reflection on Scalable ||ism

- Is solution correct … are writes exclusive?
- If data not preassigned, how does one get it
- How might this algorithm be executed for n=10,000, P=1000
- What is the performance?
- Are the properties of this solution clear from the Peril-*L* code?

Summary

- Peril-L is a useful notation for sketching a solution – you will probably implement it w/o much language support
  - Ideally, we should have language support
  - Hopefully, it helps working out subtle points, like synchronization behavior
- In algorithm design, maximizing parallelism is much less important that minimizing process-interactions

HW for Next Week

- Work out the basic logic of Sample Sort and program it in Peril-*L*
- Focus only on finding the "cuts," determining where the data goes, and "adjusting" for balanced final allocation
  - Data is initially placed where you want it – but say where that is
  - Assume any "local" functions you wish, such as `loc_sort()` that sorts data locally in place
  - n is a multiple of P, whose values are in <u>n</u> and <u>P</u>

HW Goals

- The purpose of this assignment is
  - Familiarity with Peril-*L*
  - Understand the ideas behind Sample sort
- Turn in
  - Peril-L code with “coarse grain” commenting
  - Your thoughts about the usefulness of the CTA in developing the algorithm, and any comments about Peril-*L*