Language Approaches

Parallel Language Approaches

- Existing language + parallel system calls
- Existing language augmented with parallel language constructs
- Sequential language + very smart compiler
- Totally new language and paradigm, e.g. vectors, dataflow, etc.
- “Glue” language for coordination in the large

Parallel Language Approaches

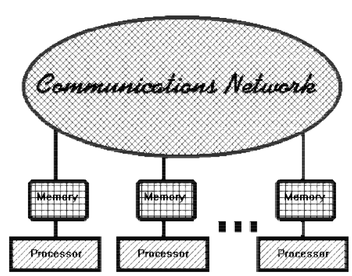
- Existing language + parallel system calls:
  MPI, PVM, pthreads, Linda, …
- Existing language augmented with parallel language constructs:
  parbegin, forall, foreach, doall, …
- Sequential language + very smart compiler
- Totally new language and paradigm, e.g. vectors, dataflow, etc.:
  NESL, ZPL, ...
- “Glue” language for coordination in the large

BSP
Bulk Synchronous Parallelism

BSP

- Bulk Synchronous Parallelism
- Model invented by Leslie Valiant at Harvard
  (Communications ACM, 33,8, Aug 1990)
- Some similarity to LogP (Berkeley), but model invented earlier
- Both a model and a library
- SPMD-style, with two types of communication
  - message-passing
  - remote DMA
- BSPlib originally implemented by Bill McColl at Oxford

Typical BSP Computer



BSP Parameters: “PLUGS”

- **P** = number of processors
- **L** = latency, cost in steps of achieving barrier synchronization
- **U** = unused (for acronym pronounceability)
- **G** = cost, in steps per word, of delivering message data (software dependent)
- **S** = processor speed (steps per second)
- (1 step is a single step on **local** data)

Improvement of G and L

- As G and L decrease, the performance becomes more scalable.
- With both equal to 1, the cost of accessing remote data is approximately the same as accessing local data and the calculation scales to the limit.

Nominal Data Points

	processors	latency	message cost	proc. Speed
Architecture	P	L (kflop)	G (flop/word)	S (mflops)
NOW (Pentium II)	10	10	30	90
SGI Power Challenge	16-512	1	10	60
Cray T-3E	32 - 2048	1	1	50

flop = “floating point operation”

kflop = 1000 flop

mflops = flop/second

Detailed measurements may be found on the BSP web site: ftp://ftp.comlab.ox.ac.uk/pub/Packages/BSP/papers/BSPparam.ps.gz

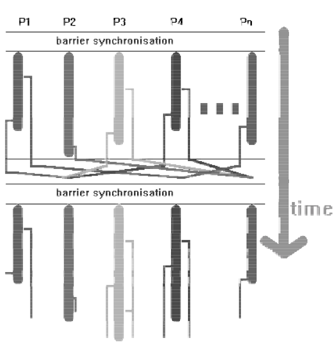
BSP Supersteps

- A superstep is a parallel set of a series of local operations, followed by a barrier synch.
- A BSP computation consists of a sequence of supersteps.

BSP

Superstep
Non-blocking
requests

Superstep
Non-blocking
requests



Superstep Time Analysis

- Let S be a superstep, and let
  - w = maximum number of steps by any one processor during S
  - h_s = max number of messages sent by any one processor during S
  - h_r = max number of messages received by any one processor during S
- Then time for S is:

  $w + G*\max(h_s,h_r) + L$

BSP Programming Abstraction

- Data requestor need only issue a **get**.
- The user does not need to buffer messages because the BSP Library will supply **buffering**, if and when it is necessary.
- Optimization of communications is handled by the BSP **library**, not the user code.

BSP C calls: Sequential followed by pure SPMD

```
int nprocs;
bsp_init(spmd_part, argc, argv);
nprocs=ReadInteger();
spmd_part();

void spmd_part()
  {
  bsp_begin(nprocs);
  … SPMD part of code ...
  bsp_end(void);
  }
```

Simple Example of Initialization and Barriers

```
void main(void)
{
  bsp_begin(bsp_nprocs());
  for (int i = 0;
       i < bsp_nprocs(); i++)
  {
    if (bsp_pid() == i)
    {
      printf("Hello from process "
          "%d of %d.\n",
          i, bsp_nprocs());
      fflush(stdout);
    }
    bsp_sync();
  }
  bsp_end();
}
```

Synchronization of a **Subset** of the Processors

- There isn't any.

PVM vs. BSP

- PVM relies on
  - having matching pairs of SENDs and RECEIVEs (fsnd & frcv)
  - the user providing buffering for messages
  - the user being aware of the type of communication in the system (ethernet, token ring, shared memory etc) and taking appropriate action to secure the best performance.
- BSP:
  - data requestor need only issue a FETCH
  - the user does not need to buffer messages because the BSP Library will supply buffering if and when it is necessary
  - optimization of communications is handled by the BSP library, not the user code.

BSP Library Functions

Class	Operation	Meaning
Initialization	bsp_begin	Start of SPMD code
	bsp_end	End of SPMD code
	bsp_init	Simulate dynamic processes
Halt	bsp_abort	One process halts all
Enquiry	bsp_nprocs	Number of processes
	bsp_pid	Find my process identifier
	bsp_time	Local time
Superstep	bsp_sync	Barrier synchronization
DRMA (Direct Remote Memory Access)	bsp_push_reg	Make area globally visible
	bsp_pop_reg	Remove global visibility
	bsp_put	Copy to remote memory
	bsp_get	Copy from remote memory
BSMP (Bulk Synchronous Message Passing)	bsp_set_tagsize	Choose tag size
	bsp_send	Send to remote queue
	bsp_get_tag	Getting the tag of a message
	bsp_move	Move from queue
High Performance	bsp_hpput	Unbuffered versions…
	bsp_hpget	..of communication
	bsp_hpmove	..primitives

Methods for Communicating

- Message passing
- Direct Remote Memory Access

Direct Remote Memory Access (DRMA)

- Remotely accessed areas must be **registered** through bsp commands.
- **bsp_push_reg** registers the start of a *local area* to be available for global remote use.
- **bsp_put** deposits local data into registered remote memory on a target processor.
- **bsp_get** copies data from registered local memory into local memory
- **bsp_pop_reg** unregisters the area

Direct Remote Memory Access

Registration

```
void bsp_push_reg(const void *ident,
             int size);
void bsp_pop_reg(const void *ident);
```

Copy to remote memory

```
void bsp_put(int pid, const void *src,
       void *dst, int offset, int nbytes);
void bsp_hpput(int pid, const void *src,
       void *dst, int offset, int nbytes);
```

Copy from remote memory

```
void bsp_get(int pid, const void *src,
       int offset, void *dst, int nbytes);
void bsp_hpget(int pid, const void *src,
       int offset, void *dst, int nbytes);
```

Example: Reverse values over array of processors

```
int reverse(int x)
{
bsp_push_reg(&x, sizeof(int));
bsp_sync();
bsp_put(bsp_nprocs() - bsp_pid() - 1, &x, &x, 0, sizeof(int));
bsp_sync();
bsp_pop_reg(&x);
return x;
}
```

Buffering Options

- **Buffered on destination**: Write at end of superstep, after all remote reads.
- **Unbuffered on destination**: Write at any time during superstep.
- **Buffered on source**: Read data from remote process at the end of a superstep, before any remote writes.
- **Unbuffered on source**: Read at any time during superstep.

Example: Sum values in a **distributed array** and redistribute to all

```
int bsp_sum(int *xs, int nelem) {
  int *local_sums,i,j,result=0;                                  local sums
  for(j=0;j<nelem;j++) result += xs[j];
  bsp_push_reg(&result,sizeof(int));
  bsp_sync();

  local_sums = calloc(bsp_nprocs(),sizeof(int));                 get remotes
  if (local_sums==NULL)
    bsp_abort("{bsp_sum} no memory for %d int",bsp_nprocs());
  for(i=0;i<bsp_nprocs();i++)
    bsp_hpget(i,&result,0,&local_sums[i],sizeof(int));
  bsp_sync();

  result=0;
  for(i=0;i<bsp_nprocs();i++) result += local_sums[i];
  bsp_pop_reg(&result);                                          sum remotes
  free(local_sums);
  return result;
}
```

Bulk Synchronous Message Passing

Choose tag size:
```
void bsp_set_tagsize (int *tag_nbytes);
```

Send to remote queue:
```
void bsp_send(int pid, const void *tag,
       const void *payload,
       int payload_nbytes);
```

Number of messages in queue:
```
void bsp_qsize(int *nmessages,
       int *accum_nbytes);
```

Getting the tag of a message:
```
void bsp_get_tag(int *status, void *tag);
```

Move from queue:
```
void bsp_move(void *payload,
       int reception_bytes);
```

A non-copying method for receiving a message:
```
int bsp_hpmove(void **tag_ptr,
       void **payload_ptr);
```

Example: All-gather of a sparse vector

```
int all_gather_sparse_vec(float *dense,int n_over_p,
                          float **sparse_out,
                          int **sparse_ivec_out){
  int global_idx,i,j,tag_size,
      nonzeros,nonzeros_size,status, *sparse_ivec;
  float *sparse;

  tag_size = sizeof(int);
  bsp_set_tagsize(&tag_size);

  bsp_sync();

  for(i=0;i<n_over_p;i++)
    if (dense[i]!=0.0) {
      global_idx = (n_over_p * bsp_pid())+i;
      for(j=0;j<bsp_nprocs();j++)
        bsp_send(j,&global_idx,&dense[i],sizeof(float));
    }
  bsp_sync();

  bsp_qsize(&nonzeros,&nonzeros_size);
  if (nonzeros>0) {
    sparse      = calloc(nonzeros,sizeof(float));
    sparse_ivec = calloc(nonzeros,sizeof(int));
    if (sparse==NULL || sparse_ivec==NULL)
      bsp_abort("Unable to allocate memory");
    for(i=0;i<nonzeros;i++) {
      bsp_get_tag(&status,&sparse_ivec[i]);
      if (status!=sizeof(float))
         bsp_abort("Should never get here");
      bsp_move(&sparse[i],sizeof(float));
    }
  }
  bsp_set_tagsize(&tag_size);
  *sparse_out      = sparse;
  *sparse_ivec_out = sparse_ivec;
  return nonzeros;
}
```

send

move

NESL

NESL: “Nested Parallelism Language”

- Guy Blelloch @ CMU
- A language coupled with a parallel complexity theory
- Functional, data-parallel, borrowing from APL, SETL, ML, Miranda, …
- Implemented on a variety of parallel machines
- Concise specification of parallel algorithms

Basis for Complexity

- Organizing by vectors makes counting easier.
- VRAM: Vector Random-Access Machine
- Similar to PRAM, but …
- Assumes **scan** (= parallel prefix) operations can be done in O(1) time.
- On a PRAM, we know this takes O(log n) time, so could just apply a log n factor to any result we obtain.
- On p << n processors, 1 VRAM is O(n/p)

Blelloch’s scan primitive

- associative binary operator $\oplus$
- identity I
- elements $a_0, a_1, \ldots, a_{n-1}$
- returns
  $[I, a_0, (a_0 \oplus a_1), \ldots, (a_0 \oplus a_1 \oplus \ldots \oplus a_{n-2})]$
- We can get, in one additional parallel $\oplus$:
  $[a_0, (a_0 \oplus a_1), \ldots, (a_0 \oplus a_1 \oplus \ldots \oplus a_{n-1})]$

Scan Examples

- arg vector: [3, 5, 2, 7, 6, 1, 4]
- results:
  - +-scan: [0, 3, 8, 10, 17, 23, 24]
  - max-scan [-∞, 3, 5, 5, 7, 7, 7]
  - min-scan [∞, 3, 3, 2, 2, 2, 1]
  - copy: [3, 3, 3, 3, 3, 3, 3]
    (what is operator and Identity?

More Scan Examples

- arg vector: [F, T, T, F, T, F, F]
- results:
  - or-scan: [F, F, T, T, T, T, T]
  - and-scan [T, F, F, F, F, F, F]

- "enumerate" operation:
  add up the number of T's to the left:
  enumerate => [0, 0, 1, 2, 2, 3, 3]

More Scan Examples

- arg vector [F, T, T, F, T, F, F]
- "enumerate-x" operation:
  add up the number of x's to the left:
  enumerate-T => [0, 0, 1, 2, 2, 3, 3]

- "back-enumerate-x" operation:
  add up the number of x's to the right:
  back-enumerate-T => [2, 2, 1, 1, 0, 0, 0]

Permutation

- permute(Vector, PermutationVector)

  permute([3, 1, 5, 1, 2, 4],
  [2, 4, 1, 0, 3, 5])

  => [1, 5, 3, 2, 1, 4]

Splitting

- Packs Vector elements corresponding to F flag in lower part, T flag in upper part:

  split([5, 7, 3, 1, 4, 2, 7, 2],
  [T, T, T, T, F, F, T, F])
  => [4, 2, 2, 5, 7, 3, 1, 7]

Exercise

- How would you implement split using scan operations?
  - Determine new index for each element:
    - Enumerate F determines indices for lower part
    - Back-enumerate T using complement vector determines indices for upper part
    - Compute vector of length- elements above
  - Select one index or the other, based upon original T-F vector
  - Permute
  - About 5 VRAM operations

Example

- split([5, 7, 3, 1, 4, 2, 6, 0],
  [T, T, T, T, F, F, T, F]):
- enumerate-F => [0, 0, 0, 0, 0, 1, 2, 2]
- back-enum-T => [4, 3, 2, 1, 1, 1, 0, 0]
- subtract back-enum from length-1 (7) => [3, 4, 5, 6, 6, 6, 7, 7]
- Select from one of the two vectors based on T-F => [3, 4, 5, 6, 0, 1, 7, 2]
- Permute => [4, 2, 0, 5, 6, 3, 1, 7]

Using split to Implement Radix Sort

- **Assume d-bit numbers**
- V = original vector of numbers;
  for I = 0 to d-1
  {
  Flags = i^{th} bit of numbers;
  V = split(V, Flags);
  }
- Time O(d) on VRAM

Representation of Nested Lists

- Customarily we use pointer structures
- Instead, NESL / VRAM uses a bit vector to represent **segment boundaries**:
- Example: The **head-flags method**
  [[3, 2, 1], [5, 7], [6, 4, 0]]
  [T, F, F, T, F, T, F, F]
- This method cannot represent empty segments however

Representation of Nested Lists

- Example: The **lengths method**
  [[3, 2, 1], [ ], [5, 7], [6, 4, 0]]
  [3, 0, 2, 4]
- Example: The **head-pointers method**
  [[3, 2, 1], [ ], [5, 7], [6, 4, 0]]
  [0, 3, 3, 5]

Segmented scan operations

- These are scan operations done separately within each segment
- Example with **head-flags method**
  [3, 2, 1, 5, 7, 6, 4, 0]
  [T, F, F,T, F, T, F, F]
- seg-+-scan =>
  [0, 3, 5, 0, 5, 0, 6, 10]

Segmented scan operations

- These are scan operations done separately within each segment
- Example with **head-flags method**
  [3, 2, 1, | 5, 7, | 6, 4, 0]
  [T, F, F, | T, F, | T, F, F]
- seg-+-scan =>
  [0, 3, 5, | 0, 5, | 0, 6, 10]

Enumerate

- Add up the number of T's to the left

Basic NESL Philosophy

- Try to convert algorithms to exploit scan primitives as much as possible:
  - O(1) VRAM computations
    - length of a Vector
    - sum of a Vector
    - permute(Vector, Index Vector)
    - p+(Vector1, Vector2) (pair-wise sum)
    - +-scan(Vector)
    - max-scan(Vector)
    - etc.

NESL Set-Patterns
(after Miranda)

- {*pattern* : *var* in *Vector*}
- {*pattern* : *var1* in *Vector1; var2* in *Vector2*}

- Example:
  - {f(x) : x in V} is essentially a map operation
  - {a + b : a in [1, 3]; b in [5, 9]} ==> [6, 12]

matrix-multiply

- matrix-multiply(A, B) =

```
{
  { sum( {x*y: x in rowA; y in colB} )
        : colB in transpose(B)
  }
  : rowA in A
}
```

Quicksort in NESL
(similar to Quicksort in SISAL)

- function qsort(a) =

```
if( #a < 2 ) then a else
  let pivot = a[#a / 2];
  lesser = {e in a : e < pivot};
  equal  = {e in a : e == pivot};
  greater = {e in a : e > pivot};
  result = {qsort(v) : v in [lesser, greater]}
  in result[0] ++ equal ++ result[1]
  $
```

Quicksort Implementation using Segmented Scan

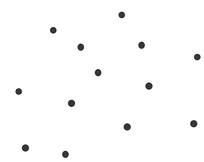
- [3, 1, 2, 7, 6, 11, 5, 4, 9, 10, 12, 8]
  pivot = 3
  [=, <, <, >, >, >, >, >, >, >, >, >]
  3-way split & segment
  [1, 2,| 3,| 7, 6, 11, 5, 4, 9, 10, 12, 8]
- segmented splits based on pivots
  [1,| 2,| 3,| 6, 5, 4,| 7,| 11, 9, 10, 12, 8]
  [1,| 2,| 3,| 4, 5,| 6,| 7,| 9, 10, 8,| 11,| 12]
- etc.

Quicksort analysis

- Worst case O(n) VRAM steps
- Average case O(log n) VRAM steps

Convex Hull Algorithm (“Quickhull”)

- Problem: Given n points in the plane, determine the subset that lie on the perimeter of the smallest convex region containing all of the points.



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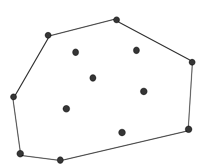
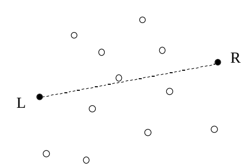


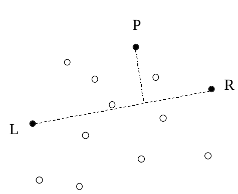
Convex Hull Algorithm (“Quickhull”)

- Begin by finding the two extrema, L and R, in the x dimension.
- L and R will be in the convex hull.
- Imagine a line between these extrema.



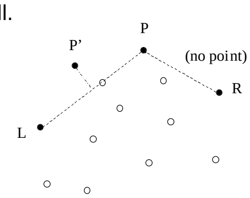
Convex Hull Algorithm (“Quickhull”)

- Find the point P above and farthest from line LR, if any.
- P will also be in the convex hull.



Convex Hull Algorithm (“Quickhull”)

- Repeat the process with lines LP and PR, until there is no point outside.
- The new points, P’, etc. are in the convex hull.



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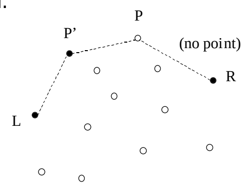
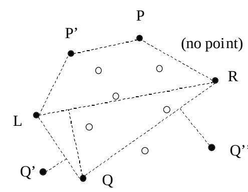
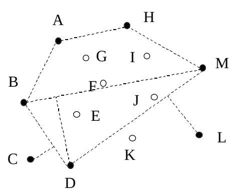


Convex Hull Algorithm (“Quickhull”)

- Meanwhile, also be doing this with points on the other side of LR (call those points Q, Q’, …)



Representation as NESL Lists



[A B C D E F G H I J K L M]

[B [A F G H I] [C D E J K L] M]

[B [A] H [C] D [E J K] L M]

[B A H C D [K] L M]

[B A H C D L M]

NESL Program for Quickhull (1)

```
% Used to find the distance of a point (o) from a line (line). %

function cross_product(o,line) =
let (xo,yo) = o;
    ((x1,y1),(x2,y2)) = line;
in (x1-xo)*(y2-yo) - (y1-yo)*(x2-xo);

% Given two points on the convex hull (p1 and p2), hsplit finds all
  the points on the hull between p1 and p2 (clockwise), inclusive of
  p1 but not of p2. %

function hsplit(points,p1,p2) =
let cross = {cross_product(p,(p1,p2)): p in points};
    packed = {p in points; c in cross | plusp(c)};
in if (#packed < 2) then [p1] ++ packed
   else
     let pm = points[max_index(cross)];
     in flatten({hsplit(packed,p1,p2): p1 in [p1,pm]; p2 in [pm,p2]});
```

NESL Program for Quickhull (2)

```
% Finds the points with minimum and maximum x coordinates, and then
  finds the upper and lower convex hull: the part clockwise from minx to
  maxx (upper) and clockwise from maxx to minx (lower). %

function convex_hull(points) =

let x = {x : (x,y) in points};
    minx = points[min_index(x)];
    maxx = points[max_index(x)];
in hsplit(points,minx,maxx) ++ hsplit(points,maxx,minx);
```

Analysis

- Similar to quicksort
- For “well-distributed” set of points, requires O(log n) VRAM steps overall.
- In worst case, can require O(n) VRAM steps.

NESL Reference Card (1)

<table>
<tr><th>Syntax</th><th>Example</th></tr>
<tr><td>FUNCTION name(args) = exp ;</td><td>FUNCTION double(a) = 2*a;</td></tr>
<tr><td>IF e1 THEN e2 ELSE e3</td><td>IF (a > 22) THEN a ELSE 5*a</td></tr>
<tr><td>LET binding* IN exp</td><td>LET a = b*6;
IN a + 3</td></tr>
<tr><td>{e1 : pattern IN e2}</td><td>{a + 22 : a IN [2, 1, 9]}</td></tr>
<tr><td>{pattern IN e1 | e2}</td><td>{a IN [2, 1, 9] | a < 8}</td></tr>
<tr><td>{e1 : p1 IN e2 ; p2 in e3}</td><td>{a + b : a IN [2,1]; b IN [7,11]}</td></tr>
</table>

Scalar Functions	
logical	not or and xor nor nand
comparison	== /= < > <= >=
predicates	plusp minusp zerop oddp evenp
arithmetic	+ - * / rem abs max min lshift rshift sqrt isqrt ln log exp expt sin cos tan asin acos atan sinh cosh tanh
conversion	btoi code_char char_code float ceil floor trunc round
random numbers	rand rand_seed
constants	pi max_int min_int

NESL Reference Card (2)

[and there's more]

Basic Sequence Functions	O(1) depth
Basic Operations	
#a	Length of a
a[i]	i^th element of a
dist(a,n)	Create sequence of length n with a in each element.
zip(a,b)	Elementwise zip two sequences together into a sequence of pairs.
[s:e]	Create sequence of integers from s to e (not inclusive of e)
[s:e:d]	Same as [s:e] but with a stride d.
Scans	
plus_scan(a)	Execute a scan on a using the + operator
min_scan(a)	Execute a scan on a using the minimum operator
max_scan(a)	Execute a scan on a using the maximum operator
or_scan(a)	Execute a scan on a using the or operator
and_scan(a)	Execute a scan on a using the and operator
Reductions	
sum(a)	Sum the elements of a
max_val(a)	Return maximum value of a
min_val(a)	Return minimum value of a
any(a)	Return true if any values of a are true.
all(a)	Return true only if all values of a are true.
count(a)	Count number of true values in a.
max_index(a)	Return position (index) of maximum value.
min_index(a)	Return position (index) of minimum value.
Reordering Functions	
read(a, i)	Read values in a from indices i
write(a, iv_pairs)	Write values in a using integer values pairs in iv_pairs
permute(a,i)	Permute elements in a to indices in i
rotate(a,i)	Rotate sequence a by i locations
reverse(a)	Reverse order of sequence a.
drop(a,i)	Drop first i elements of a.
take(a,i)	Take first i elements of a.
odd_elts(a)	Return the odd elements of a
even_elts(a)	Return the even elements of a
interleave(a,b)	Interleave the elements of a and b.
subseq(a,i,j)	Return the subsequence of a from position i to j (not inclusive of j)
a -> i	Same as read(a, i)