Language Comparisons

We’ve seen several ways to program parallel computers ... how do they compare?

Final Comments on Chapel

- Last time, Brad said regarding machine model
  - 4) A Note on Machine Model
    - As with ZPL, the CTA is still present in our design to reason about locality
    - That said, it is probably more subconscious for us
    - And we vary in some minor ways:
      ▪ no controller node -- though we do utilize a front-end launcher node in practice
      ▪ nodes can execute multiple tasks/threads -- through software multiplexing if not hardware
  
- Is that really different from what we used?
Chapel vs ZPL

- At one point Brad distinguished Chapel from ZPL by pointing out that Chapel doesn’t have a WYSIWYG performance model
  - Does it matter?
  - Can you understand how C works even though it isn’t WYSIWYG?
  - Is understanding the semantics sufficient?

Wrap Up: Issues of Compilation

- If high level languages will save us in parallel computation, then the compiler is our primary tool for making the idea work...
- How do compilers produce efficient code?
The Amazing Levialdi Shrinking Operator (1972)

- Each pixel simultaneously changes state according to the following rules

(1) A 1 bit becomes a 0 if there are 0’s to its West, NW, and North

\[
\begin{array}{c|c}
0 & 0 \\
0 & 1 \\
\end{array} \rightarrow \begin{array}{c|c}
0 & 0 \\
1 & 0 \\
\end{array}
\]

(2) A 0 bit becomes a 1 if there are 1’s to its West and North

\[
\begin{array}{c|c}
1 & X \\
0 & X \\
\end{array} \rightarrow \begin{array}{c|c}
0 & 1 \\
1 & 0 \\
\end{array}
\]

(3) All other bits remain unchanged

ZPL Solution

```
\text{... Count := 0; repeat }
\text{Next := Image \& (Image@north \| Image@nw \| Image@west);}
\text{Next := Next \| (Image@west \& Image@north \& !Image);}
\text{Conn := Next@east \| Next@se \| Next@south;}
\text{Conn := Image \& !Next \& !Conn;}
\text{Count += Conn;}
\text{Image := Next;}
\text{smore := |<< Next;}
\text{until !smore; }
\text{...}
```

8-way Connected Components

ZPL Solution

```
\text{... Count := 0; repeat }
\text{Next := Image \& (Image@north \| Image@nw \| Image@west);}
\text{Next := Next \| (Image@west \& Image@north \& !Image);}
\text{Conn := Next@east \| Next@se \| Next@south;}
\text{Conn := Image \& !Next \& !Conn;}
\text{Count += Conn;}
\text{Image := Next;}
\text{smore := |<< Next;}
\text{until !smore; }
\text{...}
```
Loop Fusion

- Lines in an array language translate into loops

\[
\text{Next:=}\text{Image} \& (\text{Image@north} \mid \text{Image@nw} \mid \text{Image@west});
\]
\[
\text{for } (i=0; i<\text{dim}_1; i++)\{
\text{for } (j=0; j<\text{dim}_2; j++)\{
\qquad /* scalar code stmt 1 */
\}
\}\]
\[
\text{Next:=}\text{Next} \mid (\text{Image@west} \& \text{Image@north} \& \neg \text{Image});
\]
\[
\text{for } (i=0; i<\text{dim}_1; i++)\{
\text{for } (j=0; j<\text{dim}_2; j++)\{
\qquad /* scalar code stmt 2 */
\}
\}\]

When the ranges match, the bodies can be merged

\[
\text{for } (i=0; i<\text{dim}_1; i++)\{
\text{for } (j=0; j<\text{dim}_2; j++)\{
\quad /* scalar code stmt 1 */
\quad /* scalar code stmt 2 */
\quad /* scalar code stmt 3 */
\quad /* scalar code stmt 4 */
\quad /* scalar code stmt 5 */
\}
\}\]

Large basic block permit much optimization
Finding the Bounding Box

- **Given**
  - X and Y are 1D arrays of coordinates such that \((X_i, Y_i)\) is a position in the coordinate plane
  - How do you compute the bounding box in ZPL?

```r
[R] begin
  rightedge := max<< X;
  topedge := max<< Y;
  leftedge := min<< X;
  bottomedge := min<< Y;
end;
```

Bounding Box Using Records

- **Using a Point Type**

```r
type point = record
  x : integer; -- x coordinate
  y : integer; -- y coordinate
end;
var Points : [1..n] point; -- points in a plane
.. .
[R] begin
  rightedge := max<< Points.x;
  topedge := max<< Points.y;
  leftedge := min<< Points.x;
  bottomedge := min<< Points.y;
end;
```
Optimizing the Communication

A key property is the regions are the same

```
[R] begin
    // rightedge := max<< Points.x;
    val1=find_local_max(Points.x);
    reduce_upsweep_max(val1);
    rightedge=catch_broadcast();
    // topedge := max<< Points.y;
    val2=find_local_max(Points.y);
    reduce_upsweep_max(val2);
    topedge=catch_broadcast();
    ...
    end;
```

Though no asymptotic benefit, performance win

```
[R] begin
    val1=find_local_max(Points.x);
    val2=find_local_max(Points.y);
    val3=find_local_min(Points.x);
    val4=find_local_min(Points.y);
    reduce_upsweep_((max,val1),(max,val2),
                    (min,val3),(min,val4));
    temp=catch_broadcast();
    rightedge=temp[0];
    topedge=temp[1];
    leftedge=temp[2];
    bottomedge=temp[3];
    end;
```
Boundary Conditions

- Data parallelism
  - Often quite regular except for the end-cases
- ZPL elevates the concept of a boundary condition

**Data parallelism**

- Often quite regular except for the end-cases

**ZPL elevates the concept of a boundary condition**

![Boundary Conditions Diagram]

### Boundary Conditions

- ***The shallow benchmark***

```c
/* Periodic boundary conditions */
[e of I]  wrap U, Uold, V, Void, P, Pold;
[s of I]  wrap U, Uold, V, Void, P, Pold;
[se of I] wrap U, Uold, V, Void, P, Pold;

C Periodic boundary conditions
uold(m+1,:n) = uold(1,:n)
vold(m+1,:n) = void(1,:n)
pold(m+1,:n) = pold(1,:n)
u(m+1,:n) = u(1,:n)
v(m+1,:n) = v(1,:n)
p(m+1,:n) = p(1,:n)
CAPR$ DO PAR on POLD<:,1>
  uold(:m,n+1) = uold(:m,1)
vold(:m,n+1) = void(:m,1)
pold(:m,n+1) = pold(:m,1)
u(:m,n+1) = u(:m,1)
v(:m,n+1) = v(:m,1)
p(:m,n+1) = p(:m,1)
  uold(m+1,n+1) = uold(1,1)
vold(m+1,n+1) = void(1,1)
pold(m+1,n+1) = pold(1,1)
u(m+1,n+1) = u(1,1)
v(m+1,n+1) = v(1,1)
p(m+1,n+1) = p(1,1)
```

**ZPL**

- Periodic boundary conditions
  - `uold(m+1,:n) = uold(1,:n)`
  - `vold(m+1,:n) = void(1,:n)`
  - `pold(m+1,:n) = pold(1,:n)`
  - `u(m+1,:n) = u(1,:n)`
  - `v(m+1,:n) = v(1,:n)`
  - `p(m+1,:n) = p(1,:n)`
Consider: Red/Black SOR

- Compute partial differential equations
- Use successive over-relaxation
- Arrange 3D values into red and black cells
- Update in place by alternately computing values for red and black cells

Two Implementations

- Regions and region operators raise the level of abstraction

```plaintext
DO nrel = 1, iter
   /* Red relaxation */
   [I with Red]  U := factor*(hsq*F + U@top + U@left + 
                  U@right + U@front + U@back);
   /* Black relaxation */
   [I without Red] U := factor*(hsq*F + U@top + U@top + U@left + 
                  U@right + U@front + U@back);
end;
```

```
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15
```
Two Implementations

- Regions and region operators raise the level of abstraction

```zpl
for nrel := 1 to nITER do
    /* Red relaxation */
    where (RED(2:NX-1,2:NY-1,2:NZ-1))
        U := factor*(hsq*F + U@top + U@bot + U@left + U@right + U@front + U@back);
    /* Black relaxation */
    [I without Red] U := factor*(hsq*F + U@top + U@left + U@right + U@front + U@back);
end;
```

Comparing HPF and ZPL

- What’s the difference in the two codes?
  - We cheated by not showing the definition of the Red mask in ZPL

- More fundamentally
  - Indexing is error prone
  - Different things should look different
    - With the explicit indices, everything looks similar
    - Why is this important?
  - Abstraction principle
    - If something is important, then it should be given a name and reused
    - Regions and directions support provide abstraction for data-parallel computation
Consider MPI

- MPI provides a wide interface
  - 12 ways to perform point-to-point communication
  - MPI 2.0 offers one-sided communication

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Sync</th>
<th>Ready</th>
<th>Buffered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>MPI_Send</td>
<td>MPI_Ssend</td>
<td>MPI_Rsend</td>
<td>MPI_Bsend</td>
</tr>
<tr>
<td>Nonblock</td>
<td>MPI_Isend</td>
<td>MPI_Issend</td>
<td>MPI_Irsend</td>
<td>MPI_Ibsend</td>
</tr>
<tr>
<td>Persistent</td>
<td>MPI_Send_init</td>
<td>MPI_Ssend_init</td>
<td>MPI_Rsend_init</td>
<td>MPI_Bsend_init</td>
</tr>
</tbody>
</table>

- Why so many choices?
- What problems does this create?

Problems with MPI’s Wide Interface

- Short term problems
  - Complicates the interface
  - Some of the specialized routines are difficult to use
    - Eg. `MPI_Rsend()` assumes that the sender and receiver are already synchronized; if not, the message is dropped on the floor
Problems with MPI’s Wide Interface

- Long term problems
  - No performance portability
  - A form of premature optimization
    - Sun E5000
    - Cray T3E

Premature Optimization

- The root of all evil
  - Requires manual changes to the application source code
  - Embeds optimizations into the source code

- Long term implications
  - Complicates maintenance
  - Defeats portability

- What’s the fundamental problem?
  - MPI is too low level
  - MPI over-specifies the communication
    - It specifies what to send, when to send it, and how to send it by specifying details of the implementation, such as the marshalling of data, synchronization, and buffering
Premature Optimization

- The root of all evil
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Why don’t compilers have this same problem?

Compiling Higher Level Languages

- Option 1: Portable compiler
  - Compile to an intermediate language, such as C+MPI

  ![Diagram of ZPL Compiler to C + MPI](image)

  **Advantages**
  - Intermediate code is portable
  - Compiler has a single backend

  **Disadvantages**
  - Favors portability over performance
  - We’re still using the MPI interface, so we have the same performance portability problems that an MPI programmer faces

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Compiling Higher Level Languages

- Option 2: Machine-specific compiler
  - Create multiple backends for multiple target platforms

- Advantages
  - Can exploit machine assumptions

- Disadvantages
  - Intermediate code is not portable
  - Lots of work in building backends

How can we resolve this conflict between portability and performance?

Ironman Interface

- A communications interface
  - A set of four calls which define constraints about possible communication
  - Individually, each call has little meaning
  - Collectively, they can be bound to different mechanisms for different machines

- The name is not based on the comic book
  - It’s a reference to Strawman, Woodman, Tinman and Ironman, . . . which were different versions of the Ada spec
The Ironman Interface: Timing

- **DR– Destination Ready**
  - Earliest point at which the destination can receive data

- **SR– Source Ready**
  - Earliest point at which the sender can transmit data

- **DN– Destination Needed**
  - Latest point at which destination can receive data

- **SV– Sender Volatile**
  - Latest point by which data must be transmitted from the sender

The Ironman Interface: Actions

- **DR– Destination Ready**
  - Assuming the destination receives data into a buffer, the receive cannot occur until the buffer has been allocated, nor can it occur while the buffer’s data is in use

- **SR– Source Ready**
  - Data cannot be sent until computed by sender

- **DN– Destination Needed**
  - The point at which the destination needs to use the data it's receiving

- **SV– Source Volatile**
  - If the sender is re-using the buffer, then this is the point at which the source’s data is no longer valid
Static Analysis– Identify Uses, Defs

- Example ZPL code

```zpl
X := D;
DR();
...
S := . . .;
SR();
...
D := S@east
DN();
Y := D;
...
SV();
S := . . .;
```

- Last use of D before data transfer
  - Cannot receive into D before this point
- Last modification of S before data transfer
  - Cannot send D before this point
- Need to receive D by this point
  - Next use of D after data transfer
- Need to send S by this point
  - Next modification of S after data transfer

Static Analysis (cont)

- Example ZPL code

```
X := D;
DR();
...
S := . . .;
SR();
...
D := S@east
DN();
Y := D;
...
SV();
S := . . .;
```

- Overall compilation scheme
  - Identify the need for communication
  - Use dependence analysis to identify Defs and Uses, which define the four points of interest
  - Perform code motion to push the four locations apart
  - Assign static Communication Tags to each set of Ironman calls
    - These tags are used to maintain state across calls at runtime
  - Insert parameters to each call

Array language semantics help by reducing control flow
### Example Bindings

**Synchronous Sends**

<table>
<thead>
<tr>
<th>Effect at $P_1$</th>
<th>SPMD code</th>
<th>Effect at $P_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>DR()</td>
<td>-</td>
</tr>
<tr>
<td>Send data from $P_1$</td>
<td>SR()</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>DN()</td>
<td>Receive data in $P_2$</td>
</tr>
<tr>
<td>-</td>
<td>SV()</td>
<td>-</td>
</tr>
</tbody>
</table>

Q: Can we bind DR() to a receive?  
A: No. It would be legal from $P_2$'s point of view, but it would cause deadlock in an SPMD program in which processes both send and receive data.

### Example Bindings II

**Non-blocking Sends and non-blocking Receives**

<table>
<thead>
<tr>
<th>Effect at $P_1$</th>
<th>SPMD code</th>
<th>Effect at $P_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>DR()</td>
<td>Non-blocking receive in $P_2$</td>
</tr>
<tr>
<td>Non-blocking send from $P_1$</td>
<td>SR()</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>DN()</td>
<td>Wait for receive at $P_2$</td>
</tr>
<tr>
<td>Wait for send to complete</td>
<td>SV()</td>
<td>-</td>
</tr>
</tbody>
</table>
### Example Bindings III

**User-Defined Callback Routines**

<table>
<thead>
<tr>
<th>Effect at P₁</th>
<th>SPMD code</th>
<th>Effect at P₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronize</td>
<td>DR()</td>
<td>Post receive callback</td>
</tr>
<tr>
<td>Send data</td>
<td>SR()</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>DN()</td>
<td>Wait for receive to complete</td>
</tr>
<tr>
<td>-</td>
<td>SV()</td>
<td>-</td>
</tr>
</tbody>
</table>

**Usage**

- This binding is similar to the use of non-blocking receives, but when the message is complete, a user-defined callback routine is called to unmarshall the data as it arrives.

### Example Bindings IV

**One-sided Communication**

<table>
<thead>
<tr>
<th>Effect at P₁</th>
<th>SPMD code</th>
<th>Effect at P₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronize</td>
<td>DR()</td>
<td>Synchronize</td>
</tr>
<tr>
<td>Put data into destination</td>
<td>SR()</td>
<td>-</td>
</tr>
<tr>
<td>Synchronize</td>
<td>DN()</td>
<td>Synchronize</td>
</tr>
<tr>
<td>-</td>
<td>SV()</td>
<td>-</td>
</tr>
</tbody>
</table>

**Usage**

- Some hardware allows one processor to Put data onto another processor’s memory.
- This mechanism is one-sided because the destination process is not involved.
### Performance Summary

- Extra procedure call overhead
  - Less than 1%
- On clusters and explicit MP machines
  - Can use MPI as envisioned by the designers
- On the Cray T3E and machines with 1-sided comm
  - One-sided communication is 60-66% faster than MPI
- On shared memory machines, use load/store
- Key benefit
  - Ironman produces code that is both portable and efficient though abstraction (dest \(\rightarrow\) source) and late binding

### The Larger Lessons?

- Higher level languages
  - Can use richer and more complicated interfaces
  - No human would want to use the Ironman interface
- Abstract interfaces
  - Abstract interfaces can convey more information than lower-level interfaces
  - Abstract interfaces can be both portable and efficient—but they need to convey the right information
  - In the case of communication, they should specify what and when to transfer data and nothing more
**MPI Summary**

- **MPI strengths**
  - Has proven to be practically useful
  - Runs on almost all parallel platforms
  - Relatively easy to implement
  - Can often serve as a building block for higher level languages

- **MPI weaknesses**
  - Too low-level of an interface
  - Limited process model
  - Forces programmer to maintain a mental map between a global view of data and multiple local views of data

---

**Break**

- In the second half we compare and contrast languages ... be prepared to comment on how the language you reviewed compares
Key criteria to evaluate any parallel programming facility:
- Correctness
- Performance
- Portability
- Scalability

We discuss criteria for evaluating languages and identify good features that we expect future languages to have ... think about how these compare with the language you reviewed

- P-Independence
  - A parallel program is \textit{P-independent} if and only if it always produces the same output on an input regardless of the number or arrangement of processes on which it is run; otherwise, it is called \textit{P-dependent}

- Global view vs Local view
  - Classify ||-programming abstractions: locks, Send/Receive, forall loops, Barrier, Reduce/Scan

How important is correctness in alg choice?
## Performance

- Performance is difficult to achieve in many cases because ...
  - <examples>
- What is the affect of \( || \)-performance on sequential execution?
- What else is there in parallel computation besides performance???
  - Does performance affect the choice of algorithm?

## Scalability

- Is scalability a concern in the the multicore world?
  - Does scalability affect the choice of algorithm?
- Good SW Engineering says that we should focus on getting the program working, and then optimize; if a program has been \( || \)-ized by focusing on the 10% of the code where all of the time is spent, do we expect it to be scalable?
It’s a basic fact of CS that computers are universal, so programs “run” on an platform. Performance portability is the term that stresses that parallel programs should “run well” everywhere:

- Is it worth it?
- Does portability affect the choice of algorithm?

Both high level
Both rest on a small number of fundamental abstractions
Both get their parallelism by data parallel evaluation of array expressions

Key difference – ZPL’s performance model gives direct info on how program will run
Nesl’s complexity model uses idealized PRAM
We have seen several concepts that we want in future languages
- Hidden parallelism
- Transparent performance
- Knowledge of Affects on Locality
- Constrained Parallelism
- Implicit vs Explicit Parallelism

Consider Each

If we didn’t have to give it another thought, we’d all be happy!
- If we can benefit from parallelism without explicitly thinking about, we win
- Find abstractions that are hand for programming but which also allow the compiler to generate parallelism
Transparent Performance

- We need to know when we’re winning and when we are losing in order to make effective algorithm choices
  - Somehow we must “see” the effects of our decisions
  - WYSIWYG may be overkill, but vague, nonexistant or inaccurate information is a barrier to effective engineering

Locality

- As with merchandizing, in parallel computing (actually, computing generally) its locality, locality, locality
- The main component of the CTA (after P) is $\lambda$ and that value must be in our mind always
- Languages must guide us to exploit locality
  - locales in Chapel
  - places in X-10
Finding the right set of facilities for parallel programming is a balancing act – enough flexibility to get the job done, but not enough to be a barrier to productivity

- Correctness impacts
- Performance impacts
- Unlimited parallelism

Allowing the compiler to find the parallelism is ideal, assuming it does a perfect job

Being able to say where the parallelism is can guarantee that we achieve it our goals of performance, scalability and portability

But neither extreme is perfect

- Multiple levels (possibly like Chapel) might be best
- Application specific with experts doing the heavy lifting might also work
Considering Languages You Reviewed

- Are there further comments regarding the languages you reviewed and the goals for the future?