Chapel: Background
Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors
- Static finite element analysis

1 TF – 1998: Cray T3E; 1,024 Processors
- Modeling of metallic magnet atoms

1 PF – 2008: Cray XT5; 150,000 Processors
- Superconductive materials

1 EF – ~2018: Cray ____; ~10,000,000 Processors
- TBD
Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors
- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

1 TF – 1998: Cray T3E; 1,024 Processors
- Modeling of metallic magnet atoms
- Fortran + MPI (Message Passing Interface)

1 PF – 2008: Cray XT5; 150,000 Processors
- Superconductive materials
- C++/Fortran + MPI + vectorization

1 EF – ~2018: Cray ____; ~10,000,000 Processors
- TBD
- TBD: C/C++/Fortran + MPI + OpenACC/OpenMP/CUDA/OpenCL

Or Perhaps Something Completely Different?
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

**Compute:** $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

**In pictures:**

\[
\begin{align*}
A & \quad = \\
B & \quad + \\
C & \quad \cdot \\
\alpha & 
\end{align*}
\]
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

**Compute:** $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

**In pictures, in parallel:**

![Diagram showing parallel computation]
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

**Compute:** $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

**In pictures, in parallel (distributed memory):**
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A, B, C$

**Compute:** $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

In pictures, in parallel (distributed memory multicore):
STREAM Triad: MPI

```c
#include <hpcc.h>

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;

    MPI_Comm_size( comm, &commSize );
    MPI_Comm_rank( comm, &myRank );

    rv = HPCC_Stream( params, 0 == myRank);
    MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

    return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
    register int j;
    double scalar;

    VectorSize = HPCC_LocalVectorSize( params, 3,
        sizeof(double), 0 );

    a = HPCC_XMALLOC( double, VectorSize );
    b = HPCC_XMALLOC( double, VectorSize );
    c = HPCC_XMALLOC( double, VectorSize );

    if (!a || !b || !c) {
        if (c) HPCC_free(c);
        if (b) HPCC_free(b);
        if (a) HPCC_free(a);
        if (doIO) {
            fprintf( outFile, "Failed to allocate memory
%d).\n", VectorSize );
            fclose( outFile );
        }
        return 1;
    }

    for (j=0; j<VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }

    scalar = 3.0;

    for (j=0; j<VectorSize; j++)
        a[j] = b[j]+scalar*c[j];

    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);

    return 0;
}
```
#include <hpcc.h>
 ifndef _OPENMP
#include <omp.h>
 endif

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;

    MPI_Comm_size( comm, &commSize );
    MPI_Comm_rank( comm, &myRank );

    rv = HPCC_Stream( params, 0 == myRank);
    MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

    return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
    register int j;
    double scalar;

    VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

    a = HPCC_XMALLOC( double, VectorSize );
    b = HPCC_XMALLOC( double, VectorSize );
    c = HPCC_XMALLOC( double, VectorSize );

    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j< VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }
    scalar = 3.0;

    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j< VectorSize; j++)
        a[j] = b[j]+scalar*c[j];

    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);

    return 0;
}
```c
#define N 2000000

int main() {
    float *d_a, *d_b, *d_c;
    float scalar;

    cudaMalloc((void**)&d_a, sizeof(float)*N);
    cudaMalloc((void**)&d_b, sizeof(float)*N);
    cudaMalloc((void**)&d_c, sizeof(float)*N);

    dim3 dimBlock(128);
    dim3 dimGrid(N/dimBlock.x);
    if( N % dimBlock.x != 0 ) dimGrid.x+=1;

    set_array<<<dimGrid,dimBlock>>>(d_b, .5f, N);
    set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);
    scalar=3.0f;
    STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar, N);
    cudaThreadSynchronize();
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);
    return 0;
}
```

```c
__global__ void set_array(float *a, float value, int len) {
    int idx = threadIdx.x + blockIdx.x * blockDim.x;
    if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad(float *a, float *b, float *c, float scalar, int len) {
    int idx = threadIdx.x + blockIdx.x * blockDim.x;
    if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```
HPC has traditionally given users...
...low-level, *control-centric* programming models
...ones that are closely tied to the underlying hardware
...ones that support only a single type of parallelism

**Examples:**

<table>
<thead>
<tr>
<th>Type of HW Parallelism</th>
<th>Programming Model</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Inter-node</td>
<td>MPI/UPC/CAF</td>
<td>executable</td>
</tr>
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<td>OpenMP/pthreads</td>
<td>iteration/task</td>
</tr>
<tr>
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<td>pragmas</td>
<td>iteration</td>
</tr>
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**benefits:** lots of control; decent generality; easy to implement
**downsides:** lots of user-managed detail; brittle to changes
# Rewinding a few slides...

## MPI + OpenMP

```c
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;
    MPI_Comm_size(comm, &commSize);
    MPI_Comm_rank(comm, &myRank);
    rv = HPCC_Stream(params, 0 == myRank);
    MPI_Reduce(&rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm);
    return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
    register int j);
    double scalar;
    VectorSize = HPCC_LocalVectorSize(params, 3, sizeof(double), 0);
    a = HPCC_XMALLOC(double, VectorSize);
    b = HPCC_XMALLOC(double, VectorSize);
    c = HPCC_XMALLOC(double, VectorSize);
    if (!a || !b || !c) {
        if (c) HPCC_free(c);
        if (b) HPCC_free(b);
        if (a) HPCC_free(a);
        if (doIO) {
            fprintf(outFile, "Failed to allocate memory (%d).\n", VectorSize);
            fclose(outFile);
        }
        return 1;
    }
    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j<VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }
    scalar = 3.0;
    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j<VectorSize; j++)
        a[j] = b[j] + scalar * c[j];
    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);
    return 0;
}
#endif
```

## CUDA

```c
#define N 2000000

int main() {
    float *d_a, *d_b, *d_c;
    float scalar;
    cudaMemcpy((void**)&d_a, sizeof(float)*N);
    cudaMemcpy((void**)&d_b, sizeof(float)*N);
    cudaMemcpy((void**)&d_c, sizeof(float)*N);

    dim3 dimBlock(128);
    dim3 dimGrid(N/dimBlock.x);
    if (N % dimBlock.x != 0) dimGrid.x+=1;

    cudaMemcpy((void**)&d_b, .5f, N);
    cudaMemcpy((void**)&d_c, .5f, N);
    cudaMemcpy((void**)&d_a, scalar, N);

    cudaThreadSynchronize();
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);
}
```

### HPC suffers from too many distinct notations for expressing parallelism and locality

```c
if( N % dimBlock.x != 0 ) dimGrid.x+=1;

set_array<<<dimGrid,dimBlock>>>(d_b, .5f, N);
set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);

scalar=3.0f;
STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar, N);
cudaThreadSynchronize();

cudaFree(d_a);
cudaFree(d_b);
cudaFree(d_c);
```

```c
__global__ void set_array(float *a, float value, int len) {
    int idx = threadIdx.x + blockIdx.x * blockDim.x;
    if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad(float *a, float *b, float *c, float scalar, int len) {
    int idx = threadIdx.x + blockIdx.x * blockDim.x;
    if (idx < len) c[idx] = a[idx] + scalar * b[idx];
}
```
STREAM Triad: Chapel

```chapel
config const m = 1000,
    alpha = 3.0;

const ProblemSpace = {1..m} dmapped ...;

var A, B, C: [ProblemSpace] real;

B = 2.0;
C = 3.0;
A = B + alpha * C;
```

Philosophy: Good language design can tease details of locality and parallelism away from an algorithm, permitting the compiler, runtime, applied scientist, and parallel expert to each focus on their strengths.
Outline

- Chapel’s Context
- Chapel’s Motivating Themes
  1. General parallel programming
  2. Global-view abstractions
  3. Multiresolution design
  4. Control over locality/affinity
  5. Reduce gap between mainstream & HPC languages
With a unified set of concepts...

...express any parallelism desired in a user’s program

- **Styles**: data-parallel, task-parallel, concurrency, nested, ...
- **Levels**: model, function, loop, statement, expression

...target all parallelism available in the hardware

- **Types**: machines, nodes, cores, instructions

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2) Global-View Abstractions

In pictures: "Apply a 3-Point Stencil to a vector"

\[
\begin{align*}
\text{Global-View} & \quad \text{Local-View} \\
( & \quad ( \\
+ & \quad )/2 \\
= & \quad 
\end{align*}
\]
In pictures: “Apply a 3-Point Stencil to a vector”
2) Global-View Abstractions

In code: “Apply a 3-Point Stencil to a vector”

**Global-View**

```chapel
proc main() {
    var n = 1000;
    var A, B: [1..n] real;
    forall i in 2..n-1 do
        B[i] = (A[i-1] + A[i+1])/2;
}
```

**Local-View (SPMD)**

```chapel
proc main() {
    var n = 1000;
    var p = numProcs(),
        me = myProc(),
        myN = n/p,
    var A, B: [0..myN+1] real;
    if (me < p-1) {
        send(me+1, A[myN]);
        recv(me+1, A[myN+1]);
    }
    if (me > 0) {
        send(me-1, A[1]);
        recv(me-1, A[0]);
    }
    forall i in 1..myN do
        B[i] = (A[i-1] + A[i+1])/2;
}
```

**Bug:** Refers to uninitialized values at ends of A
2) Global-View Abstractions

In code: “Apply a 3-Point Stencil to a vector”

```
Global-View

proc main() {
    var n = 1000;
    var A, B: [1..n] real;

    forall i in 2..n-1 do
        B[i] = (A[i-1] + A[i+1])/2;
}

Local-View (SPMD)

proc main() {
    var n = 1000;
    var p = numProcs(),
        me = myProc(),
        myN = n/p,
        myLo = 1,
        myHi = myN;
    var A, B: [0..myN+1] real;

    if (me < p-1) {
        send(me+1, A[myN]);
        recv(me+1, A[myN+1]);
    } else
        myHi = myN-1;
    if (me > 0) {
        send(me-1, A[1]);
        recv(me-1, A[0]);
    } else
        myLo = 2;

    forall i in myLo..myHi do
        B[i] = (A[i-1] + A[i+1])/2;
}

Communication becomes geometrically more complex for higher-dimensional arrays

Assumes p divides n
```
2) Global-View Programming: A Final Note

- A language may support both global- and local-view programming — in particular, Chapel does

```chapel
proc main() {
    coforall loc in Locales do
        on loc do
            MySPMDProgram(loc.id, Locales.numElements);
}

proc MySPMDProgram(me, p) {
    ...
}
```
3) Multiresolution Language Design: Motivation

“Why is everything so difficult?”

“Why don’t my programs port trivially?”

“Why don’t I have more control?”
Multiresolution Design: Support multiple tiers of features

- higher levels for programmability, productivity
- lower levels for greater degrees of control

Chapel language concepts

- Domain Maps
- Data Parallelism
- Task Parallelism
- Base Language
- Locality Control
- Target Machine

- build the higher-level concepts in terms of the lower
- permit the user to intermix layers arbitrarily
Consider:

- Scalable architectures package memory near processors
- Remote accesses take longer than local accesses

Therefore:

- Placement of data relative to computation affects scalability
- Give programmers control of data and task placement

Note:

- As core counts grow, locality will matter more on desktops
- GPUs and accelerators already expose node-level locality
Consider:

- Students graduate with training in Java, Matlab, Perl, Python
- Yet HPC programming is dominated by Fortran, C/C++, MPI

We’d like to narrow this gulf with Chapel:

- to leverage advances in modern language design
- to better utilize the skills of the entry-level workforce...
- ...while not ostracizing the traditional HPC programmer
  - e.g., support object-oriented programming, but make it optional
Questions?

- Chapel’s Context
- Chapel’s Motivating Themes
  1. General parallel programming
  2. *Global-view* abstractions
  3. *Multiresolution* design
  4. Control over locality/affinity
  5. Reduce gap between mainstream & HPC languages