Enabling Parallel Computing in Chapel with Clang and LLVM

Michael Ferguson
Cray Inc.

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Outline

- Introducing Chapel
- C interoperability
- Combined Code Generation
- Communication Optimization in LLVM

What is Chapel?

Chapel: A productive parallel programming language

- portable
- open-source
- a collaborative effort

Goals:

- Support general parallel programming
  - “any parallel algorithm on any parallel hardware”
- Make parallel programming at scale far more productive

What does “Productivity” mean to you?

Recent Graduates:

“something similar to what I used in school: Python, Matlab, Java, …”

Seasoned HPC Programmers:

“that sugary stuff that I don’t need because I ~~was born to suffer”~~

want full control to ensure performance”

Computational Scientists:

“something that lets me express my parallel computations without having to wrestle with architecture-specific details”

Chapel Team:

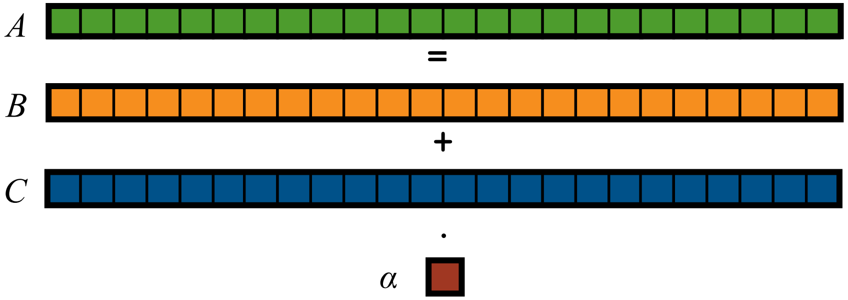
“something that lets computational scientists express what they want, without taking away the control that HPC programmers want, implemented in a language as attractive as recent graduates want.”

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:



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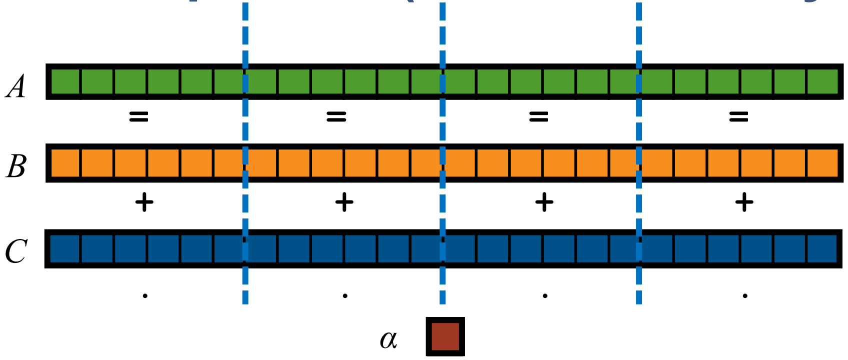
In pictures, in parallel (shared memory / multicore):



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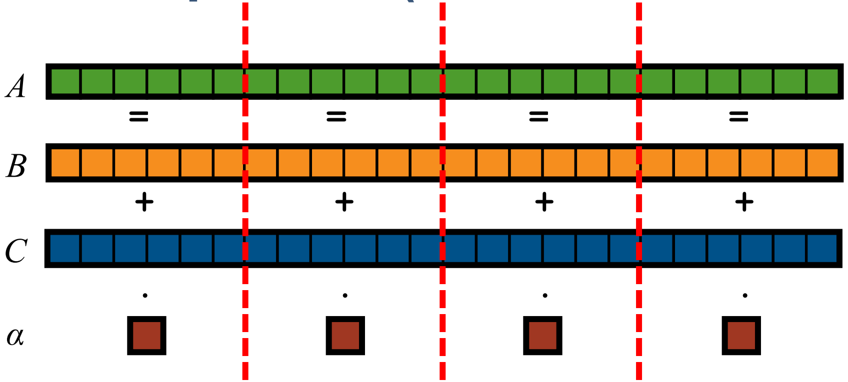

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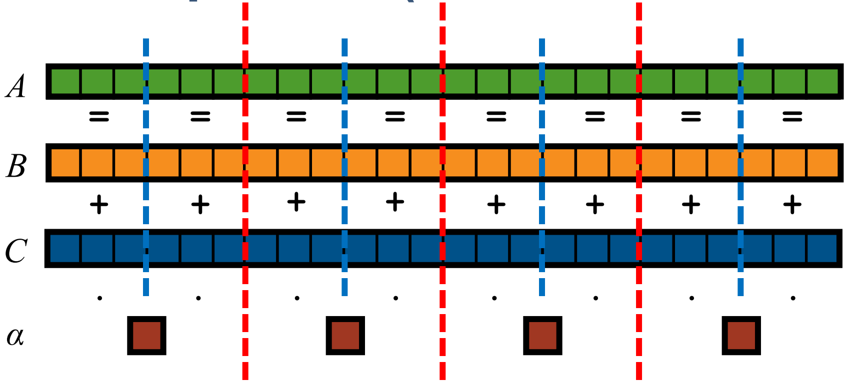
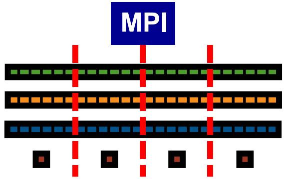


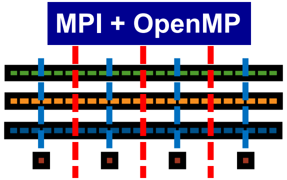
STREAM Triad: MPI




```
#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] = 1.0;
}
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;  }
```

STREAM Triad: 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;

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```

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    if (doIO) {
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        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] = 1.0;
  }
  scalar = 3.0;

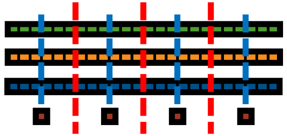
#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

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

  return 0;  }
```

STREAM Triad: MPI+OpenMP

MPI + OpenMP



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int HPCC_StarStream(HPCC_Params *params) {
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}

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```
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  }
  scalar = 3.0;

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

  HPCC_free(c);
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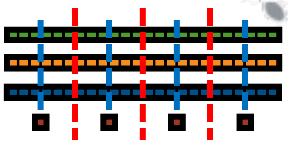
  return 0;  }
```

CUDA



```
#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

  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();

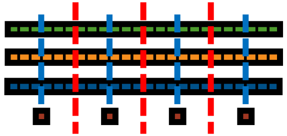
  cudaFree(d_a);
  cudaFree(d_b);
  cudaFree(d_c);


__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: MPI+OpenMP

MPI + OpenMP



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

```
  return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
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  a = HPCC_XMALLOC( double, VectorSize );
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      fclose( outFile );
    }
    return 1;
  }
```

```
  }
  scalar = 3.0;

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

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  HPCC_free(b);
  HPCC_free(a);

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```
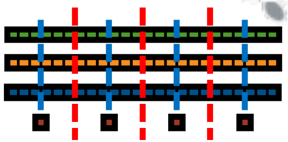

CUDA



```
#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 );
```

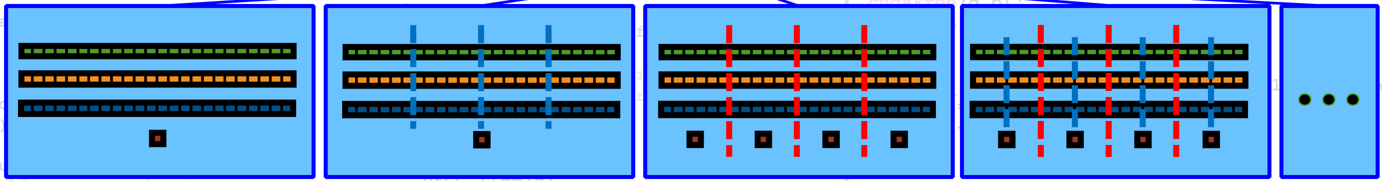
```
  cudaThreadSynchronize();

  cudaFree(d_a);
  cudaFree(d_b);
  cudaFree(d_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 suffers from too many distinct notations for expressing parallelism and locality.
This tends to be a result of bottom-up language design.

STREAM Triad: Chapel

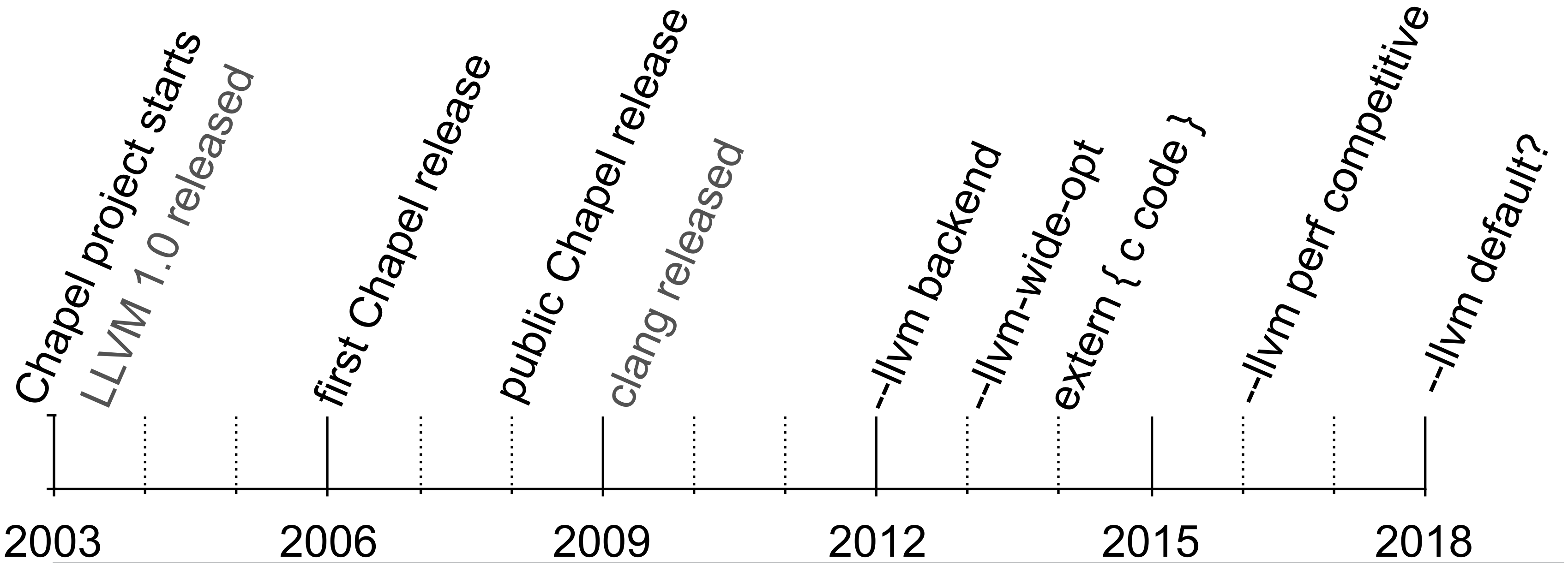
```
use …;

config const m = 1000,
             alpha = 3.0;

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

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

B = 2.0;
C = 1.0;

A = B + alpha * C;
```

The special sauce: How should this index set—and any arrays and computations over it—be mapped to the system?



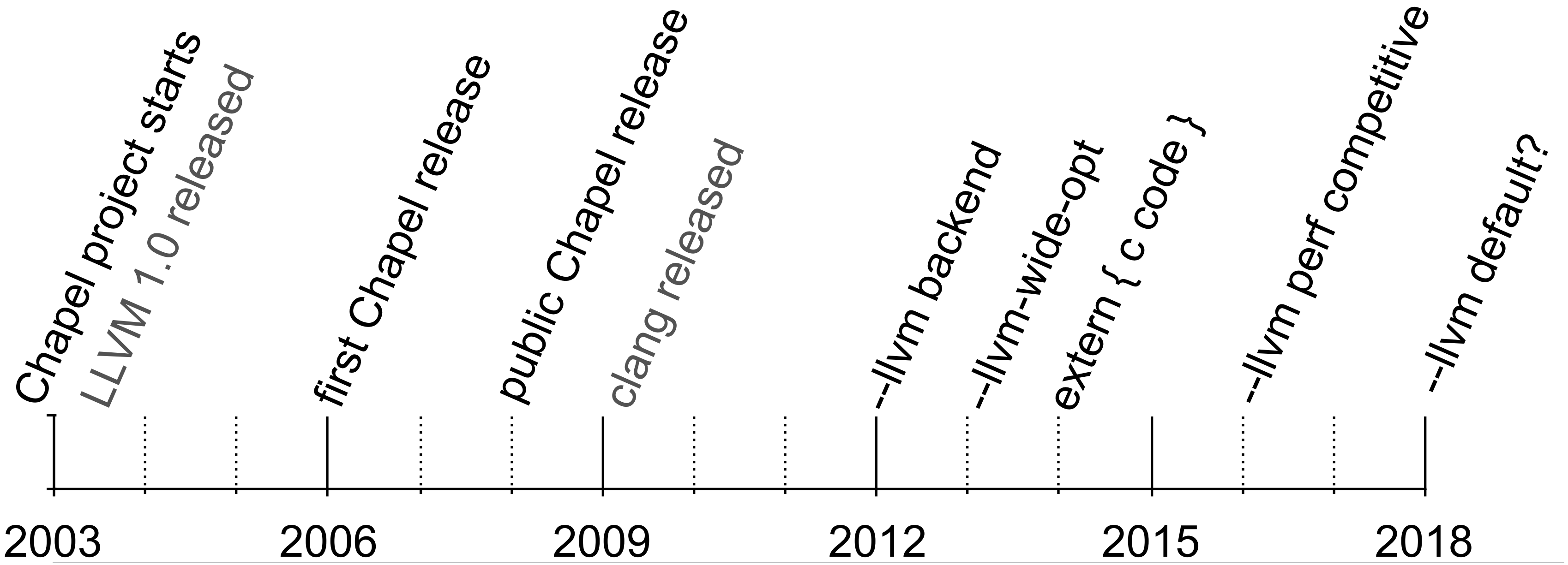
Philosophy: Good, *top-down* language design can tease system-specific implementation details away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

Chapel+LLVM History

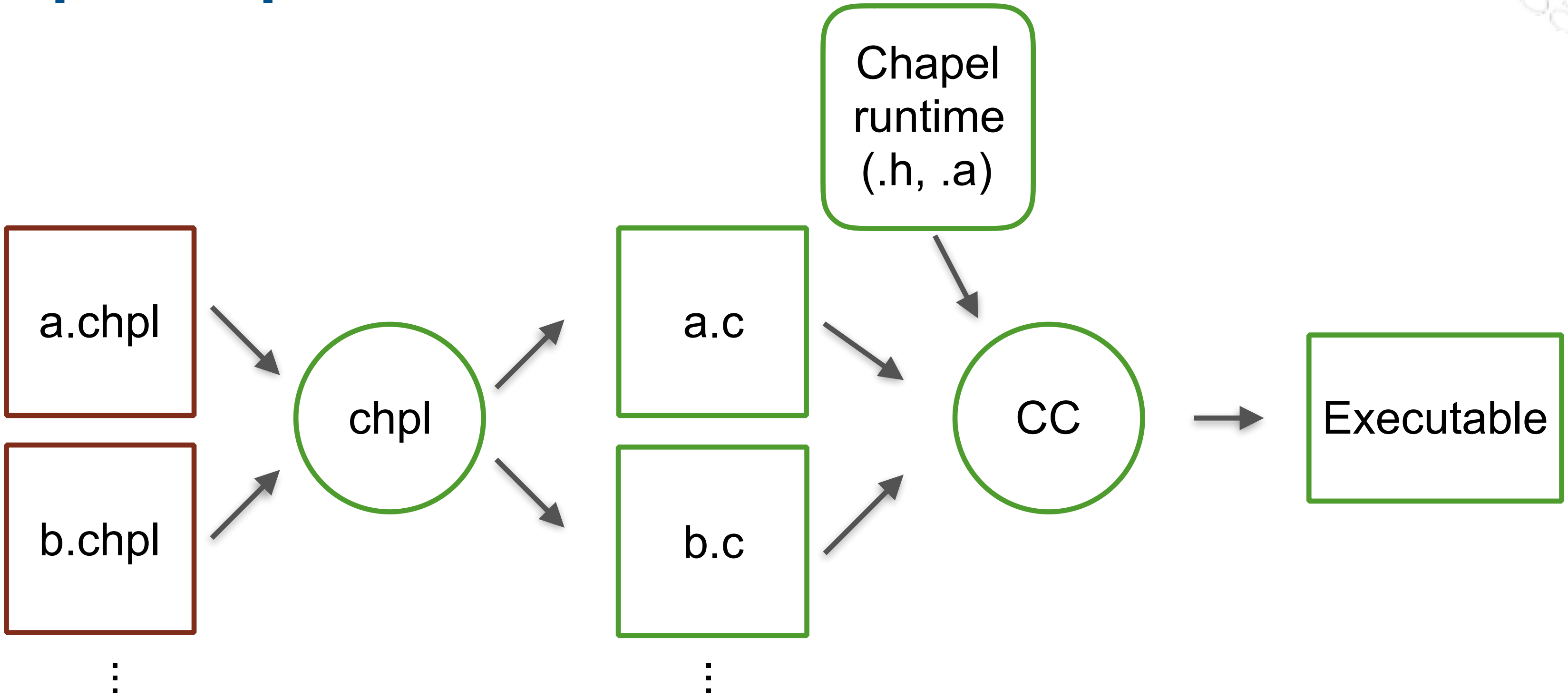


Chapel+LLVM History

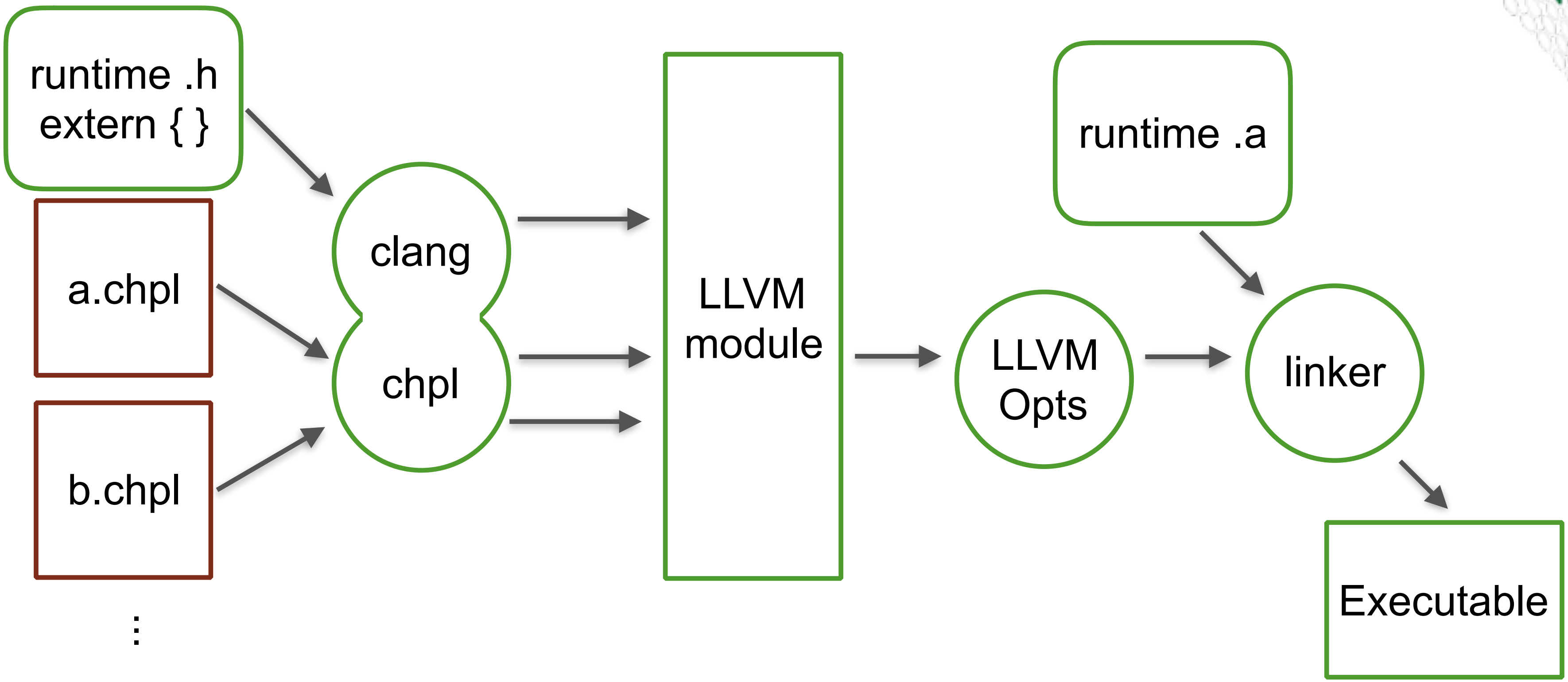
- Chapel project grew up generating C code



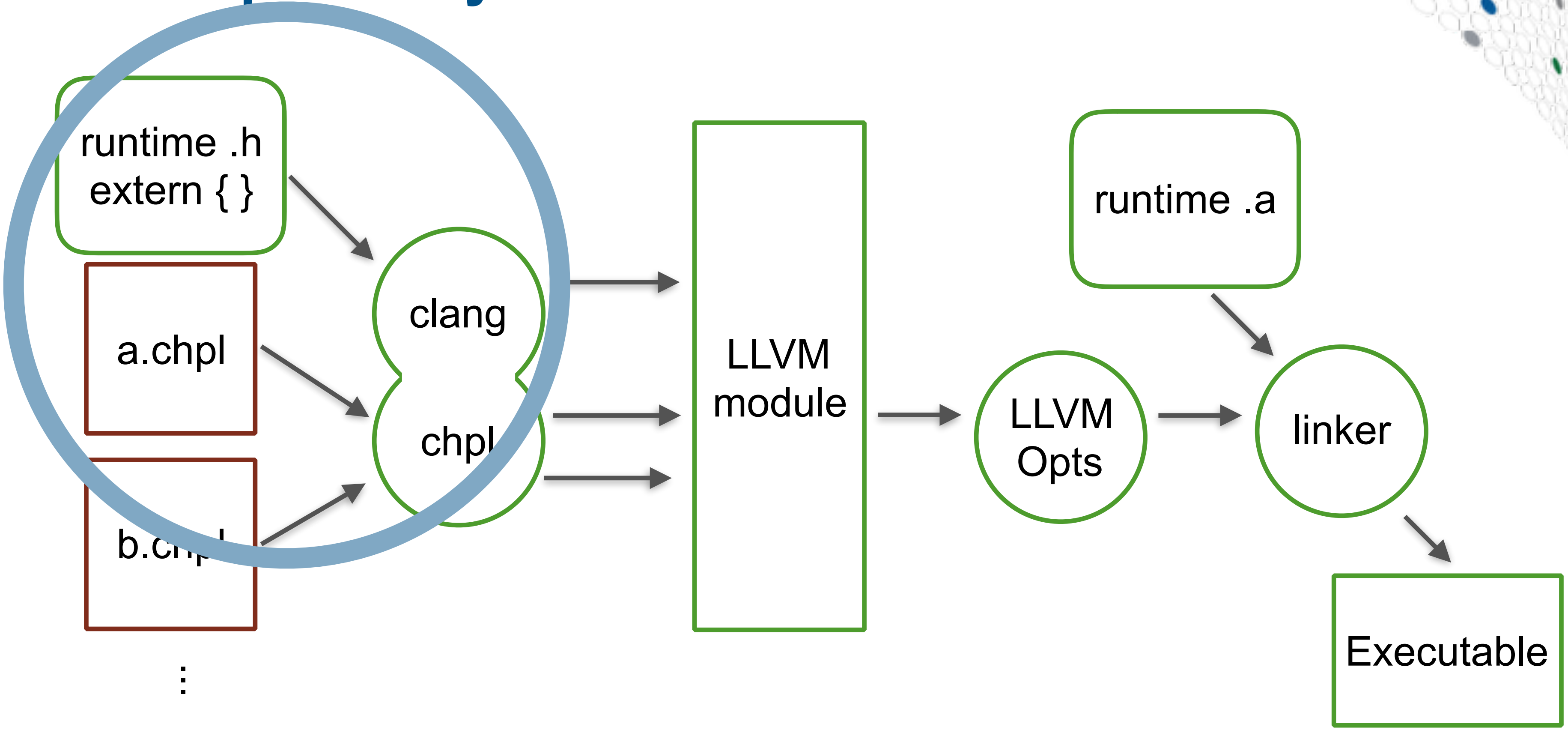
chpl compilation flow



chpl --llvm compilation flow



C Interoperability



Goals of C Interoperability

- Chapel is a new language
- Libraries are important for productivity

➡ Easy use of libraries in another language is important!

- Chapel supports interoperability with C
- Need to be able to use an existing C library
  - functions, variables, types, and macros
- Using C functions needs to be efficient
  - performance is a goal here!

C Interoperability Example

// add1.h

```
static inline
int add1(int x) { return x+1; }
```

// addone.chpl

```
extern proc add1(x:c_int):c_int;
writeln(add1(4));
```

```
$ chpl addone.chpl add1.h
$ ./addone
5
```

With extern { }

// add1.h

```
static inline
int add1(int x) { return x+1; }
```

// addone.chpl

```
extern { #include “add1.h” }
writeln(add1(4));
```

```
$ chpl addone.chpl
$ ./addone
5
```

extern block compilation flow

frontend passes

parse .chpl

readExternC

⋮

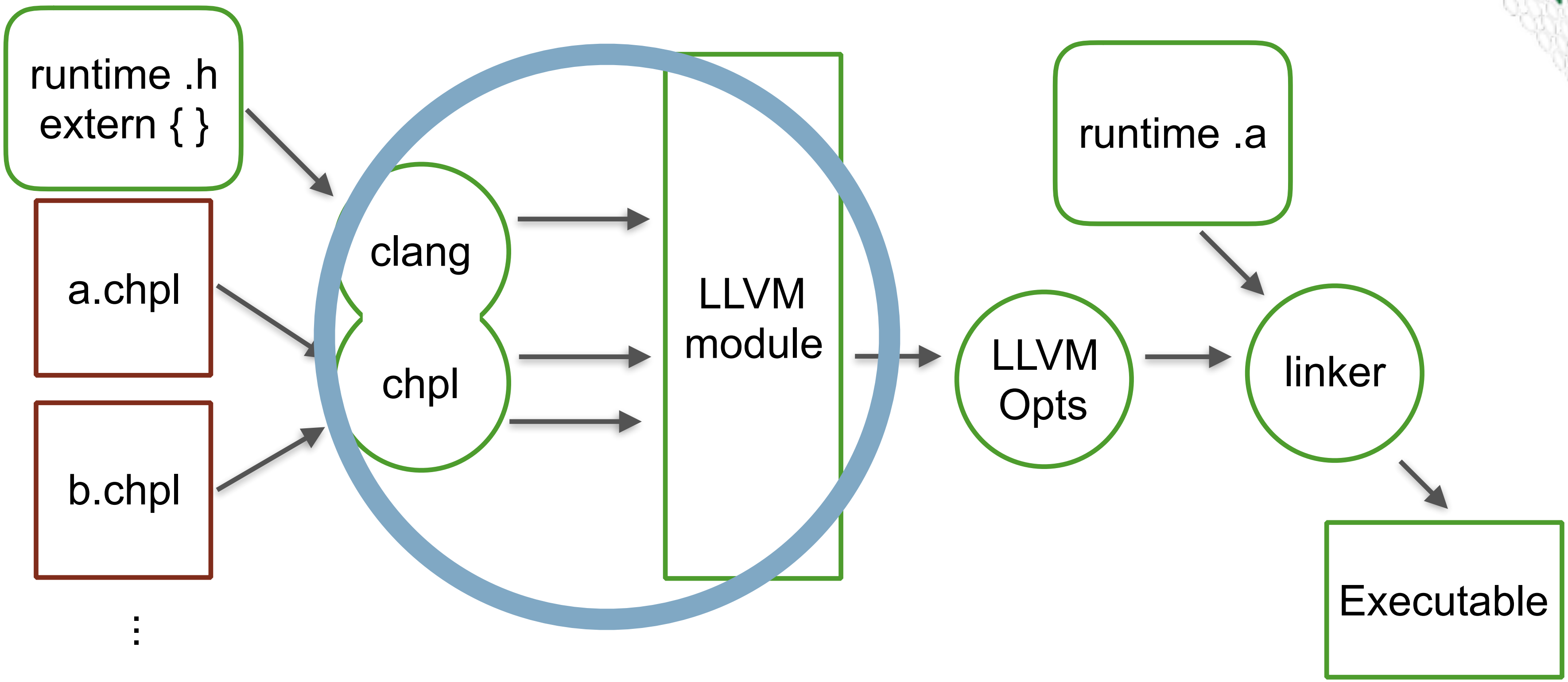
extern {
  int add1(**int** x);
}

clang parse:
C ➡ clang AST

readExternC:
clang AST ➡ chapel extern decls

extern proc add1(x:**c_int**):**c_int**;

Combined Code Generation



Inlining with C code

- Some C functions expect to be inlined
  - if not, there is a performance penalty
- Runtime is written primarily in C
  - Enabling easy use of libraries like qthreads
- Chapel uses third-party libraries such as GMP
  - Library authors control what might be inlined
- Since Chapel generated C, it became normal to assume:
  - functions can be inlined
  - C types are available
  - fields in C structs are available
  - C macros are available

Example: Accessing a Struct Field

// sockaddr.h

```
#include <sys/socket.h>
typedef struct my_sockaddr_s {
  struct sockaddr_storage addr;
  size_t len;
} my_sockaddr_t;
```

// network.chpl

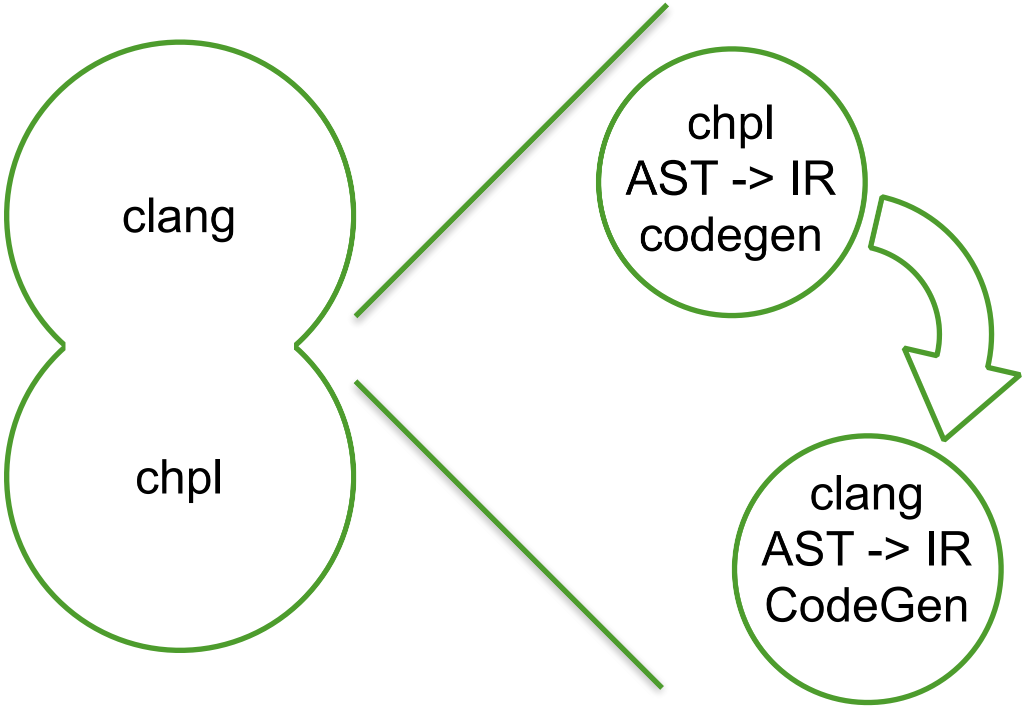
```
require "sockaddr.h";
extern record my_sockaddr_t {
  var len: size_t;
}
```

OR

```
extern { #include “sockaddr.h” }
```

```
var x:my_sockaddr_t;
x.len = c_sizeof(c_int);
writeln(x.len);
```

Implementing Combined Code Generation



Call to C proc? Use of C global?
  GetAddrOfGlobal
Use of extern type?
  *CodeGen::convertTypeForMemory**
Use of field in extern record?
  *CodeGen::getLLVMFieldNumber***

* *new to clang 5*
** *will be new in clang 6*

C Macros

// usecs.h

```
#define USECS_PER_SEC 1000000
```

// microseconds.chpl

```
require "usecs.h";
const USECS_PER_SEC:c_int;
config const secs = 1;
writeln(secs, " seconds is ",
        secs*USECS_PER_SEC,
        " microseconds");
```

```
$ chpl macrodemo.chpl
$ ./macrodemo
5
```

How can this work when we generate LLVM IR?

'forall' parallelism

- The earlier example used

```
A = B + alpha * C
```

- Which is equivalent to:

```
forall (a,b,c) in zip(A,B,C) do
  a = b + alpha * c;
```

- Chapel's forall loop represents a data parallel loop
  - iterations can run in any order
  - typically divides iterations up among some tasks
  - parallelism is controlled by what is iterated over

'forall' lowering (1)

```
// user-code.chpl
forall x in MyIter() {
  body(x);
}
```

\+

```
// library.chpl
iter MyIter(...) {
  coforall i in 1..n do  // creates n tasks
    for j in 1..m do
      yield i*m+j;    }
```

```
coforall i in 1..n do
  for j in 1..m do
    body(i*m+j);
```

'forall' lowering (2)

```
coforall i in 1..n do
  for j in 1..m do
    body(i*m+j);
```

```
count = n
for i in 1..n do
  spawn(taskfn, i)
wait for count == 0
```

```
proc taskfn(i) {
  for j in 1..m do
    body(i*m+j);
}
```

Could be represented in a parallel LLVM IR

Vectorizing

- We'd like to vectorize 'forall' loops
- Recall, 'forall' means iterations can run in any order
- Two strategies for vectorization:

A. Vectorize in Chapel front-end
   - Chapel front-end creates vectorized LLVM IR
   - Challenges: not sharing vectorizer, might be a deoptimization

B. Vectorize in LLVM optimizations (LoopVectorizer)
   - Chapel front-end generates loops with parallel_loop_access
   - Challenges: user-defined reductions, querying vector lane

Vectorizing in the Front-End

- It would be lower level than most front end operations
  - a lot depends on the processor:
    - vector width
    - supported vector operations
    - whether or not vectorizing is profitable
- Front-end vectorization reasonable if details are simple
- Presumably there is a reason that vectorization normally runs late in the LLVM optimization pipeline...
- Misses out on a chance to share with the community

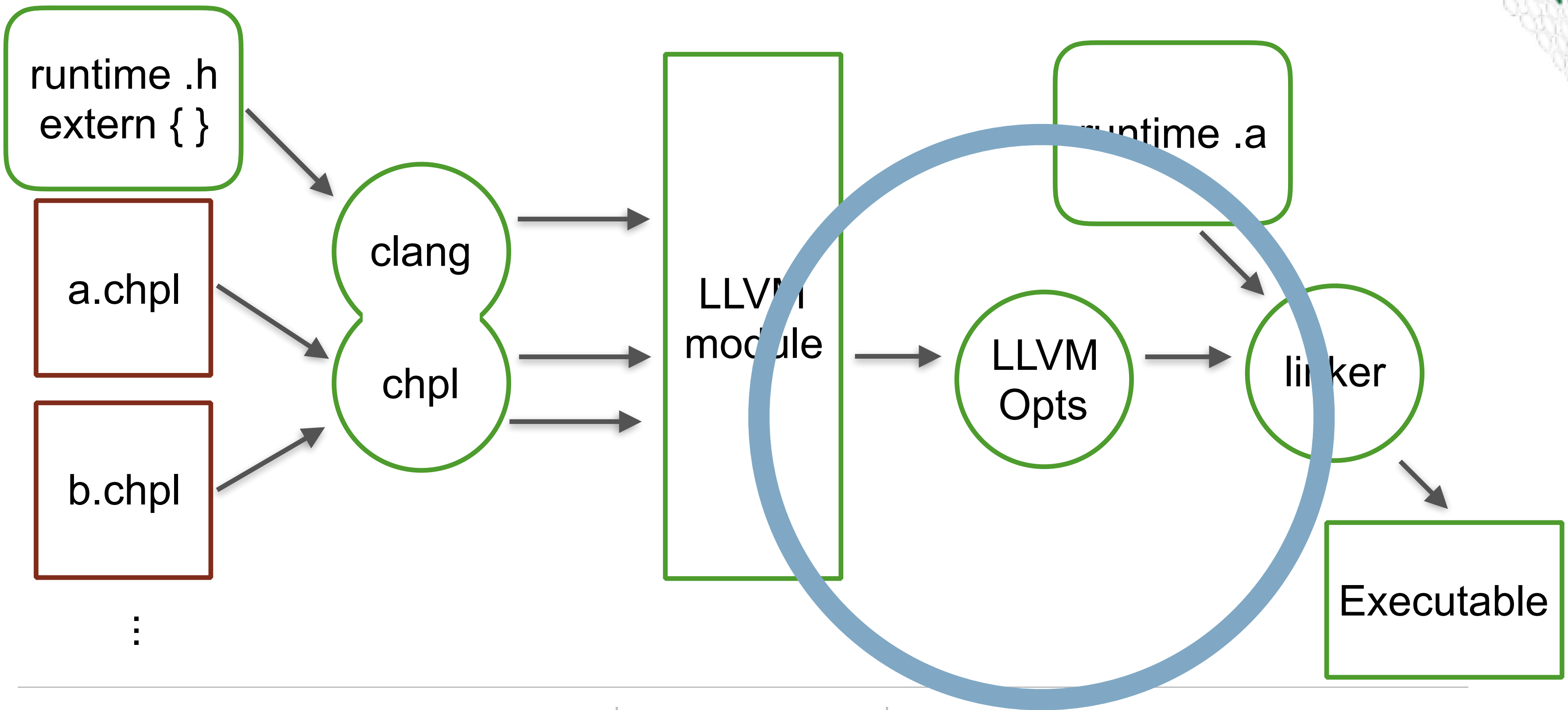
Vectorizing in as an LLVM optimization

- parallel_loop_access good for most of loop body...
- ... but what about user-defined reductions?
- Would opaque function calls help?
  - front-end generates opaque_accumulate function calls
  - after vectorization, these are replaced with real reduction ops
  - vectorizer would see something like this:

```
define opaque_accumulate(...) readnone
for ... {
   load/stores with parallel_loop_access ...
   %acc = opaque_accumulate(%acc, %value)
}
```

  - Would it interfere too much with the vectorizer? Harm cost modelling?
- Does LLVM need a canonical way to express custom reductions?

Communication Optimization in LLVM



Aside: Introducing PGAS Communication

Parallelism and Locality: Distinct in Chapel

- This is a parallel, but local program:

```
coforall i in 1..msgs do
  writeln("Hello from task ", i);
```

- This is a distributed, but serial program:

```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do writeln("Hello from locale 2!");
```

- This is a distributed parallel program:

```
coforall i in 1..msgs do
  on Locales[i%numLocales] do
    writeln("Hello from task ", i,
            " running on locale ", here.id);
```

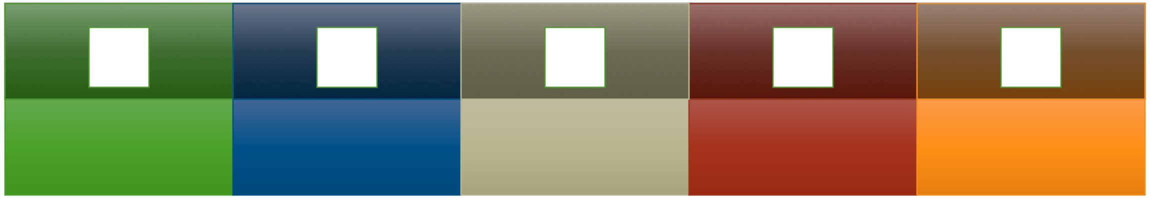
Partitioned Global Address Space (PGAS) Languages
(Or more accurately: partitioned global namespace languages)

- abstract concept:
  - support a shared namespace on distributed memory
    - permit parallel tasks to access remote variables by naming them
  - establish a strong sense of ownership
    - every variable has a well-defined location
    - local variables are cheaper to access than remote ones
- traditional PGAS languages have been SPMD in nature
  - best-known examples: Fortran 2008's co-arrays, Unified Parallel C (UPC)

SPMD PGAS Languages (using a pseudo-language, not Chapel)

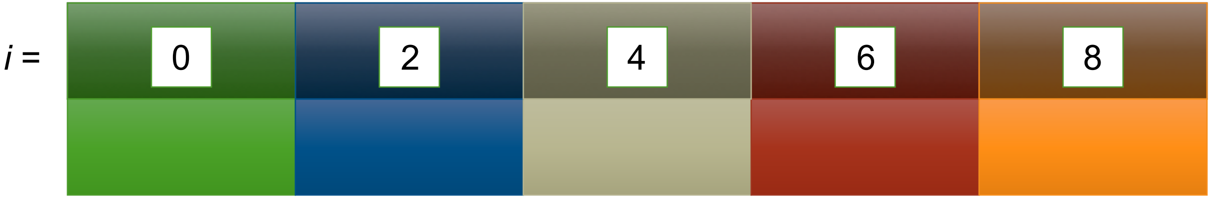
```
shared int i(*);            // declare a shared variable i
```

i =



SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
shared int i(*);             // declare a shared variable i
function main() {
  i = 2*this_image();        // each image initializes its copy
```



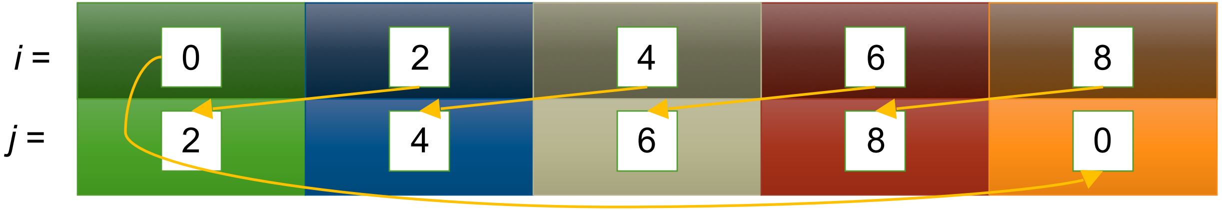
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
shared int i(*);                 // declare a shared variable i
function main() {
  i = 2*this_image();            // each image initializes its copy

  private int j;                 // declare a private variable j
```

i =	0	2	4	6	8
j =					

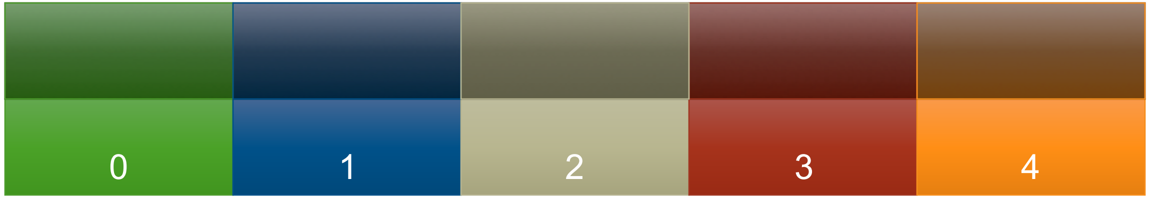
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
shared int i(*);            // declare a shared variable i
function main() {
  i = 2*this_image();       // each image initializes its copy
  barrier();
  private int j;            // declare a private variable j
  j = i( (this_image()+1) % num_images() );
    // ^^ access our neighbor's copy of i; compiler and runtime implement the communication
    // Q: How did we know our neighbor had an i?
    // A: Because it's SPMD – we're all running the same program so if we have an i, so do they.
```



Chapel and PGAS

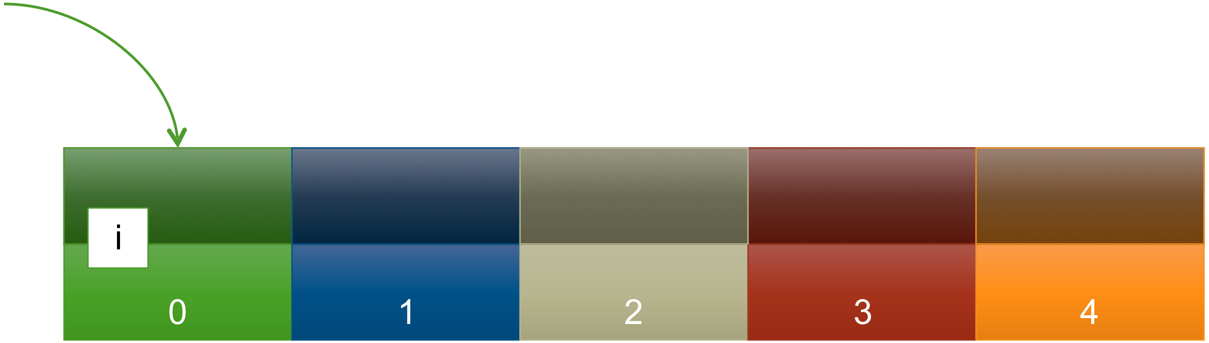
- Chapel is PGAS, but unlike most, it's not inherently SPMD
  - never think about "the other copies of the program"
  - "global name/address space" comes from lexical scoping
    - as in traditional languages, each declaration yields one variable
    - variables are stored on the locale where the task declaring it is executing



Locales (think: "compute nodes")

Chapel: Scoping and Locality

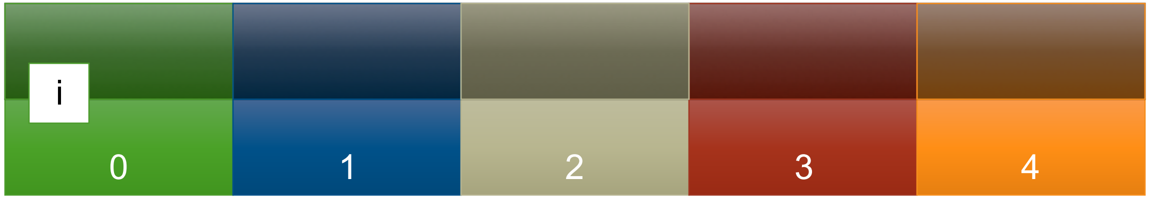
```
var i: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

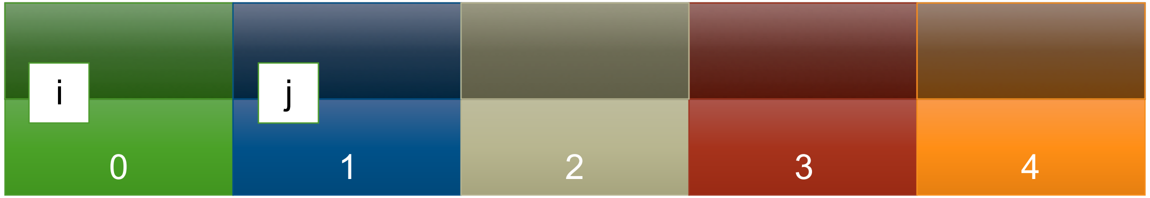
```
var i: int;
on Locales[1] {
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

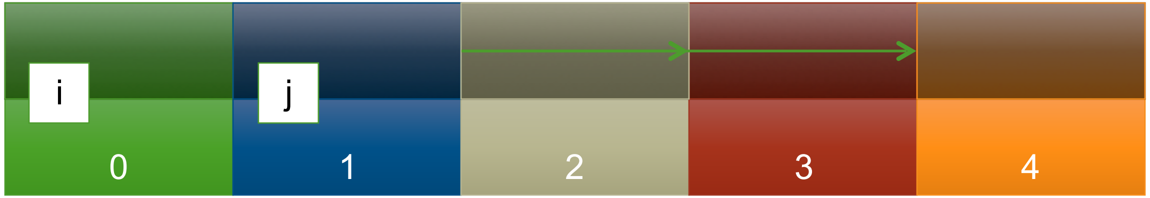
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

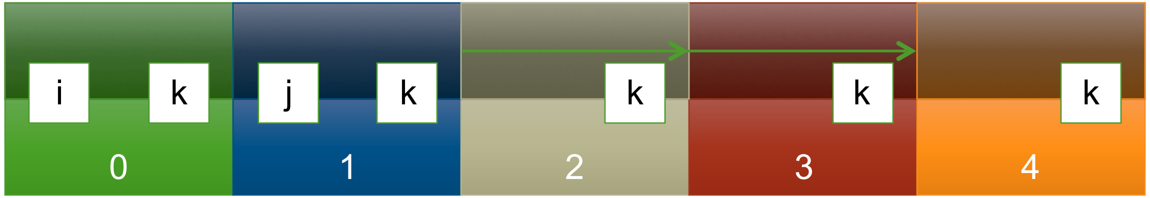
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

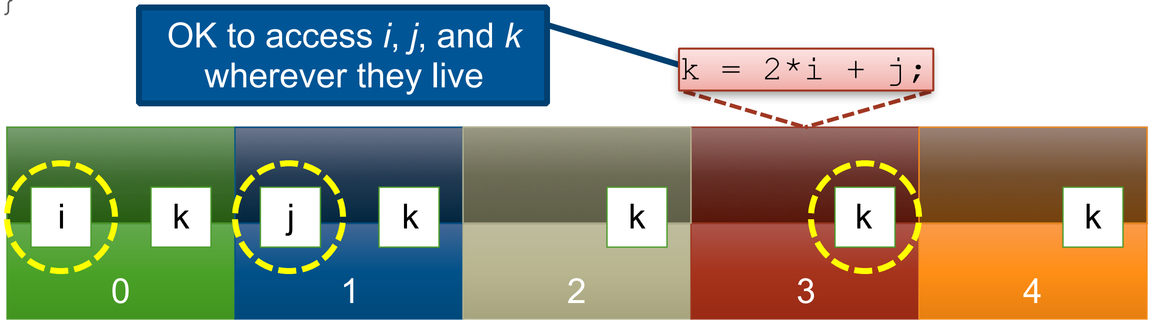
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      …
    }
  }
}
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      k = 2*i + j;
    }
  }
}
```

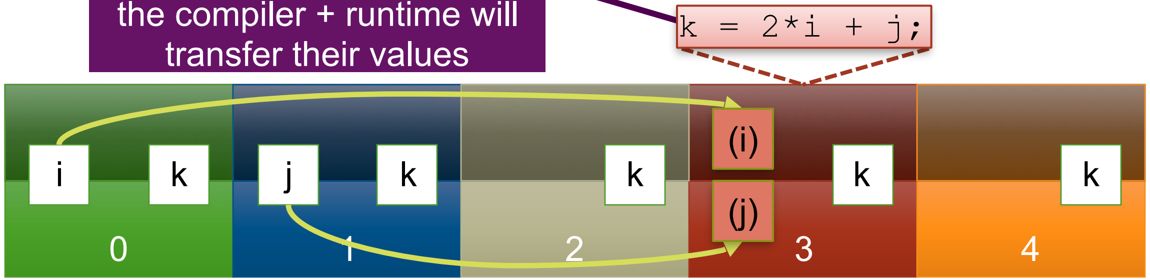


Locales (think: "compute nodes")

Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      k = 2*i + j;
    }
  }
}
```

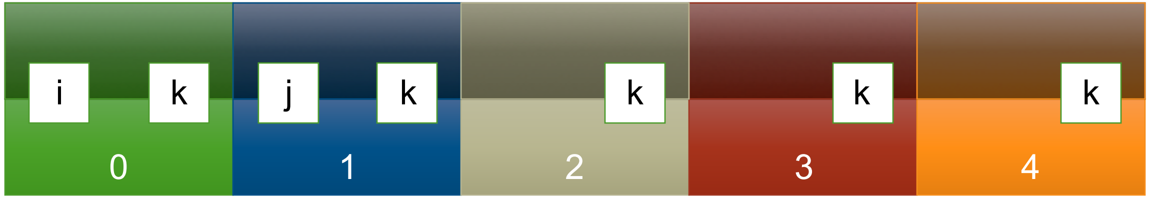
here, *i* and *j* are remote, so the compiler + runtime will transfer their values



Locales (think: “compute nodes”)

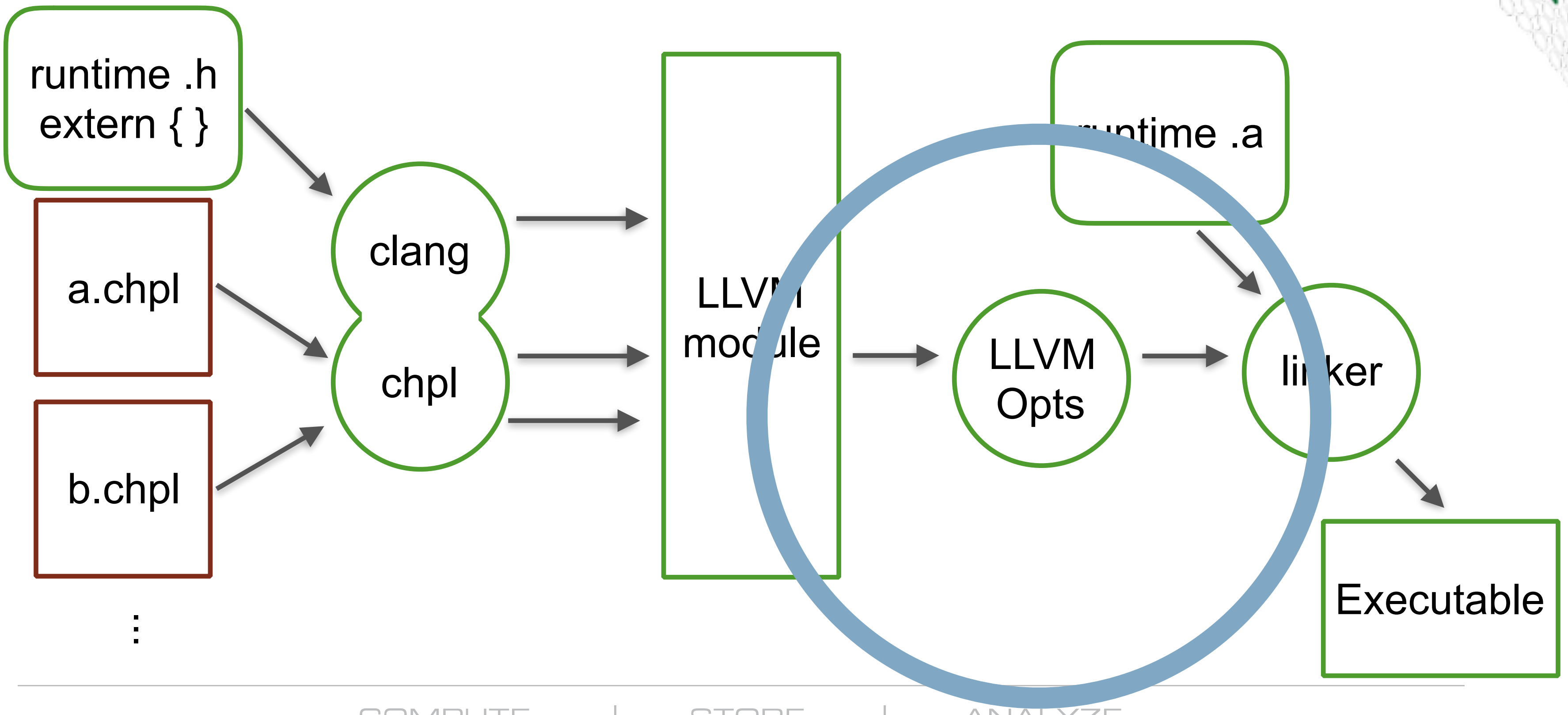
Chapel: Locality queries

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;

      ...here...          // query the locale on which this task is running
     ...j.locale...       // query the locale on which j is stored
    }
  }
}
```



Locales (think: "compute nodes")

Communication Optimization in LLVM



Communication Optimization: Overview

- Idea is to use LLVM passes to optimize GET and PUT
- Enabled with --llvm-wide-opt compiler flag
- First appeared in Chapel 1.8
- Unfortunately was not working in 1.15 and 1.16 releases

Communication Optimization: In a Picture

```
// x is possibly remote
var sum = 0;
for i in 1..100 {
  %1 = get(x);
  sum += %1;
}
```

TO GLOBAL MEMORY

```
var sum = 0;
for i in 1..100 {
  %1 = load <100> %x
  sum += %1;
}
```

EXISTING LLVM OPTIMIZATION LICM

```
var sum = 0;
%1 = load <100> %x
for i in 1..100 {
  sum += %r1;
}
```

TO DISTRIBUTED MEMORY

```
var sum = 0;
%1 = get(x);
for i in 1..100 {
  sum += %1;
}
```

```
load <100> %x = load i64 addrspace(100)* %x
```

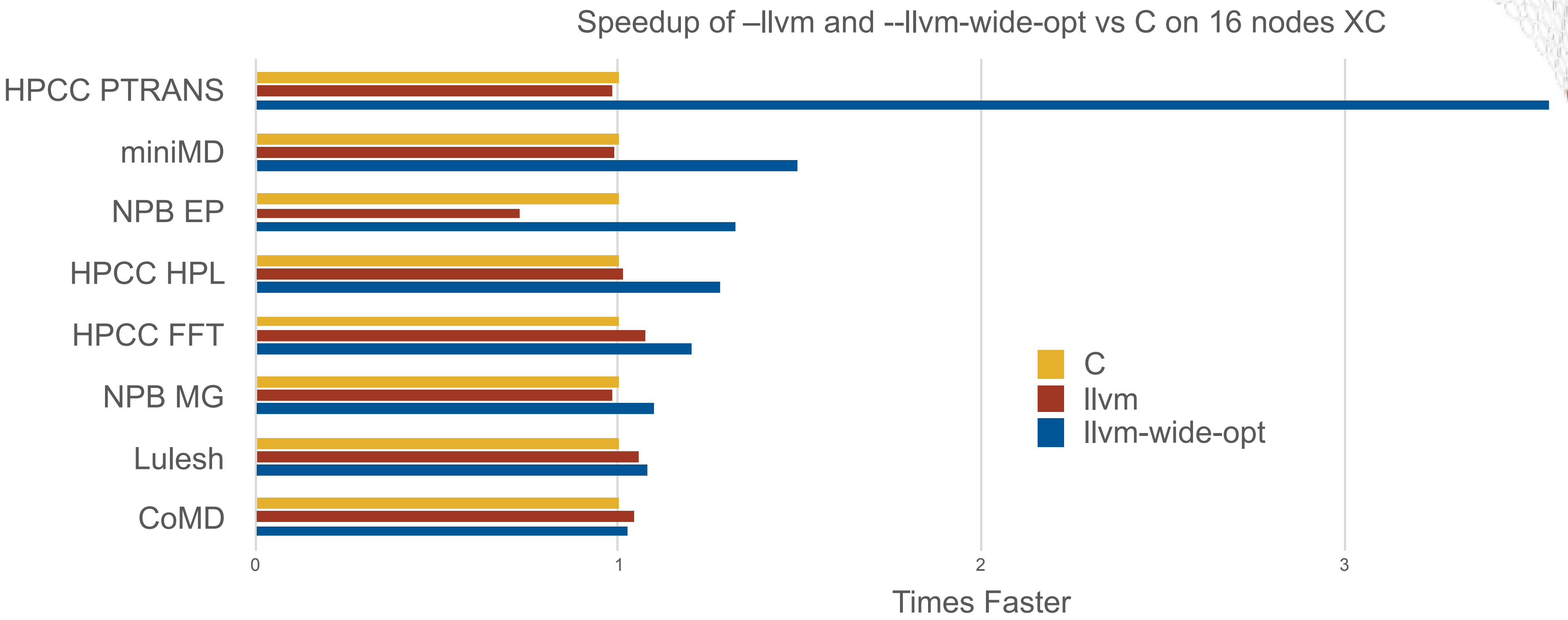
Communication Optimization: Details

- Uses existing LLVM passes to optimize GET and PUT
  - GET/PUT represented as load/store with special pointer type
  - normal LLVM optimizations run and optimize load/store as usual
  - a custom LLVM pass lowers them back to calls to the Chapel runtime
- Optimization gains from this strategy can be significant
  - See "LLVM-based Communication Optimizations for PGAS Programs"
- Historically, needed packed wide pointers as workaround
  - wide pointer normally stored as a 128-bit struct: {node id, address}
  - bugs in LLVM 3.3 prevented using 128-bit pointers
  - packed wide pointers store node id in high bits of a 64-bit address
  - led to scalability constraints - maximum of 65536 nodes
  - sometimes made --llvm-wide-opt code slower than C backend

Communication Optimization: Recent Work

- Fixed --llvm-wide-opt
- Removed reliance on packed wide pointers
- Now generates LLVM IR with 128-bit pointers
  - revealed (only) a few LLVM bugs (so far)
    - BasicAA - needed to use APInt more (not just int64_t)
    - ValueTracking - error using APInt

Comm Opt: Impact



Future Work

- Chapel 1.17 - hope to make --llvm the default
- Migrate some Chapel-specific optimizations to LLVM
- Continue improving the LLVM IR that Chapel generates
- Separate compilation & link-time optimization
- Chapel interpreter using LLVM JIT
- Using a shared parallel LLVM IR

Thanks

- Thanks for your
  - attention
  - great discussions
  - patch reviews
  - related work!

- Check us out at https://chapel-lang.org

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Backup Slides

Chapel Community R&D Efforts

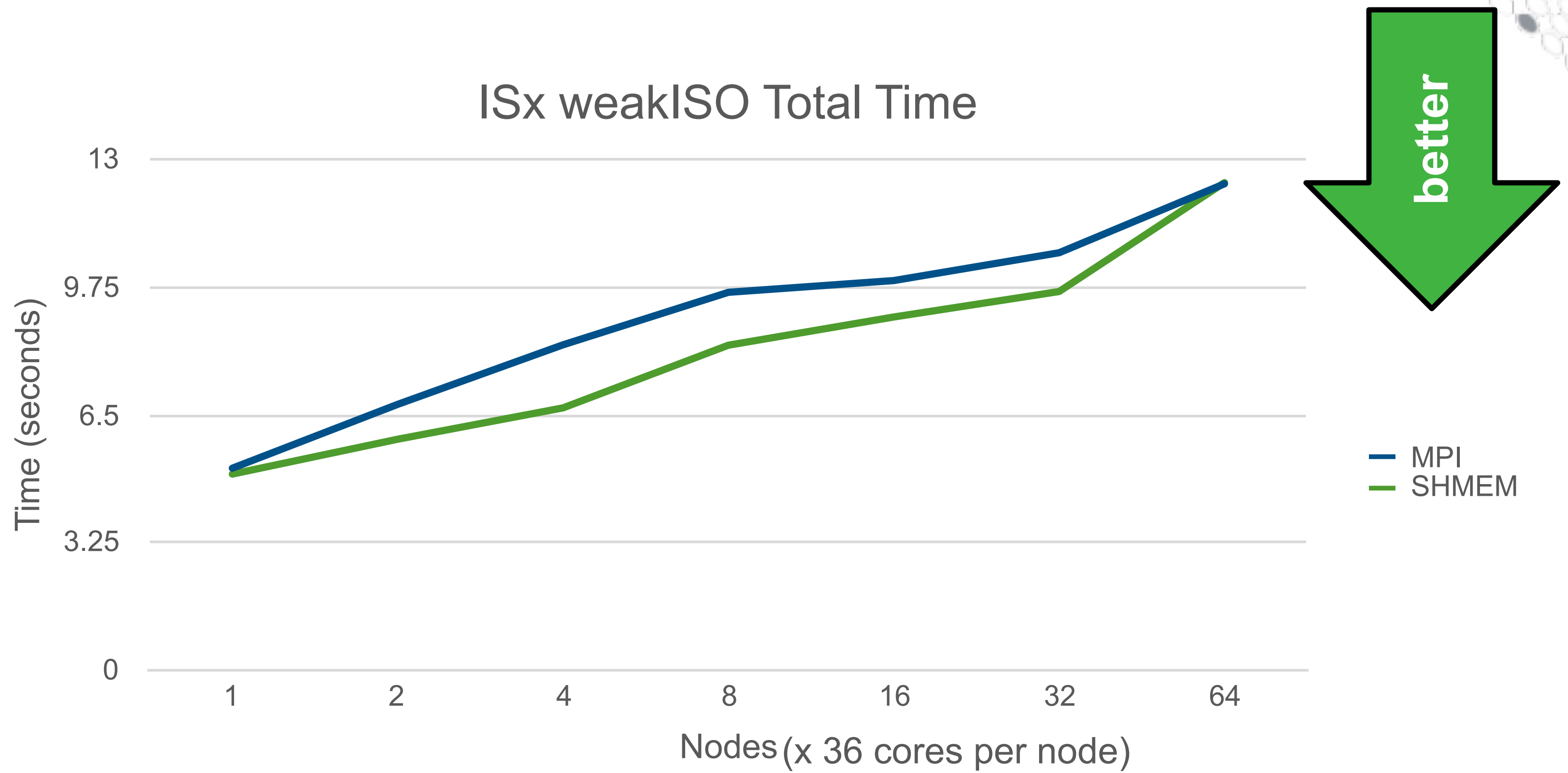
(and several others…)

http://chapel.cray.com/collaborations.html

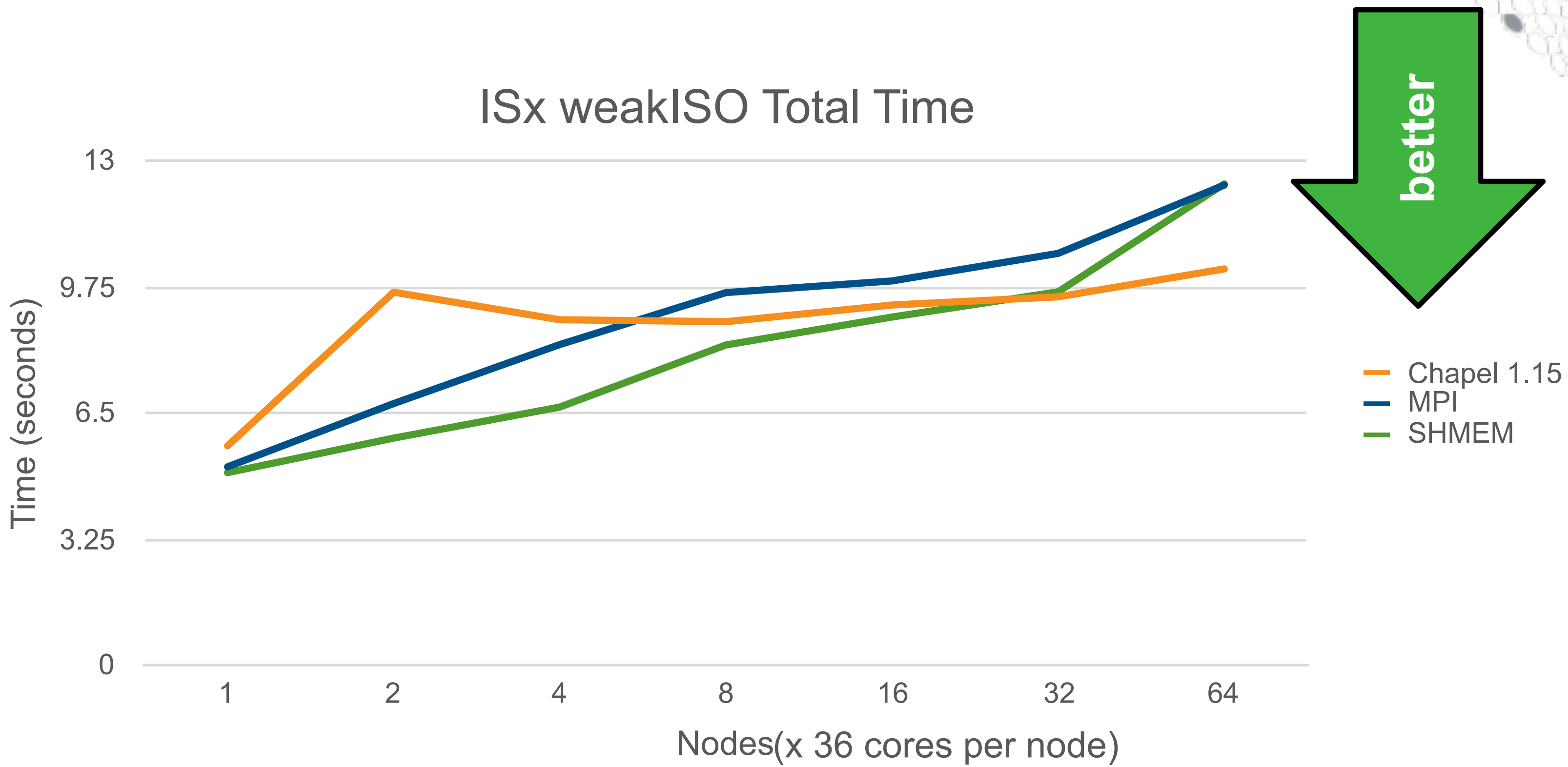
Contributions to LLVM/clang

- Add clang CodeGen support for generating field access
  - supports 'extern record'
  - https://reviews.llvm.org/D38473
- Fix a bug in BasicAA – crashing with 128-bit pointers
  - enables --llvm-wide-opt with {node, address} wide pointers
  - https://reviews.llvm.org/D38499
- Fix a bug in ValueTracking – crashing with 128-bit pointers
  - enables --llvm-wide-opt with {node, address} wide pointers
  - https://reviews.llvm.org/D38501

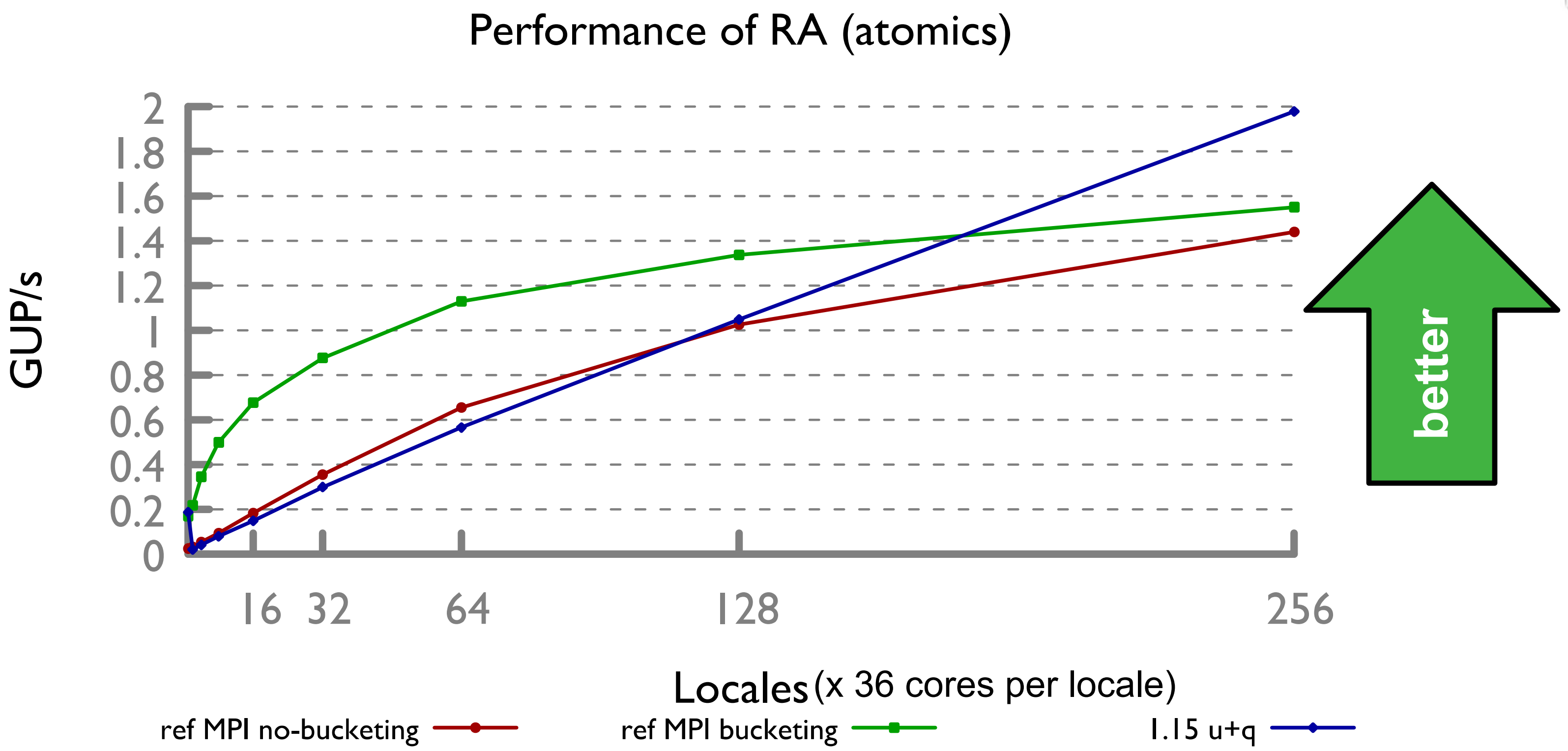
ISx Execution Time: MPI, SHMEM



ISx Execution Time: MPI, SHMEM, Chapel



RA Performance: Chapel vs. MPI

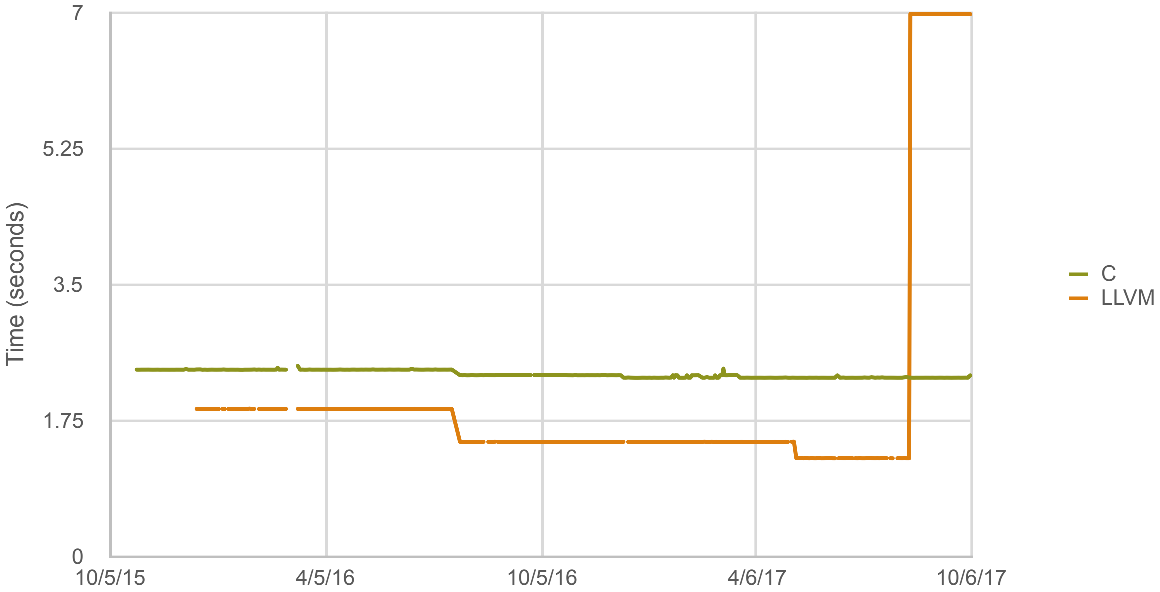


Chapel+LLVM - Google Summer of Code

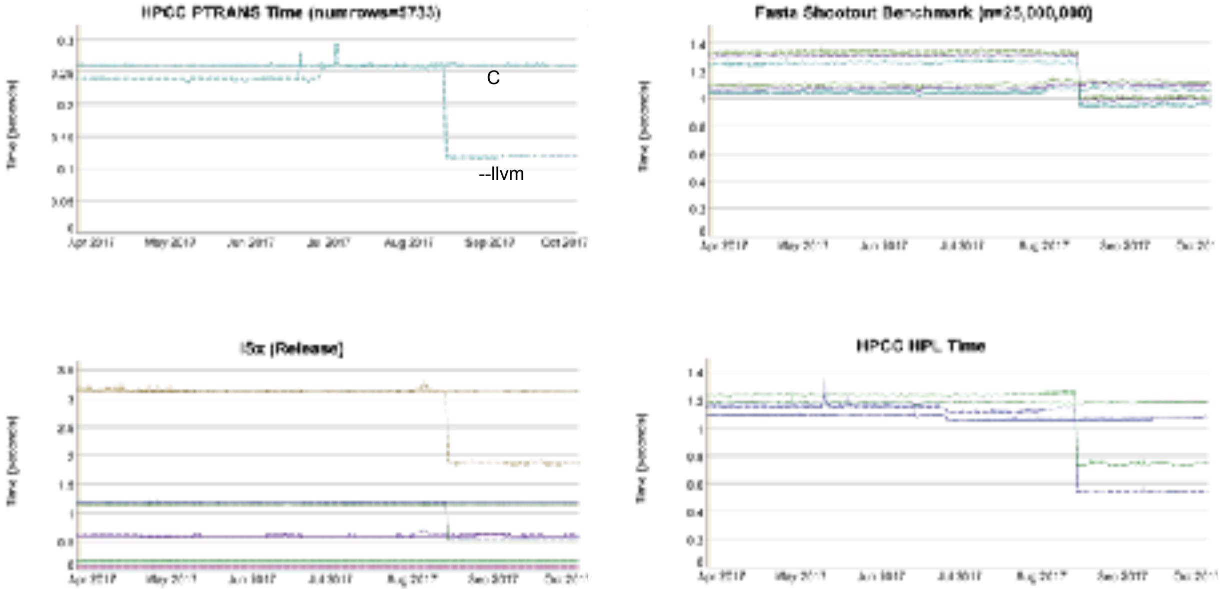
- Przemysław Leśniak contributed many improvements:
  - mark signed integer arithmetic with 'nsw' to improve loop optimization
  - command-line flags to emit LLVM IR at particular points in compilation
  - new tests that use LLVM tool FileCheck to verify emitted LLVM IR
  - mark order-independent loops with llvm.parallel_loop_access metadata
  - mark const variables with llvm.invariant.start
  - enable LLVM floating point optimization when --no-ieee-float is used
  - add nonnull attribute to ref arguments to functions
  - add a header implementing clang built-ins to improve 'complex' performance

Performance Regression: LLVM 3.7 to 4 upgrade

LCALS find_first_min went from 2x faster than C to 3x slower



Performance Improvements: LLVM 3.7 to 4

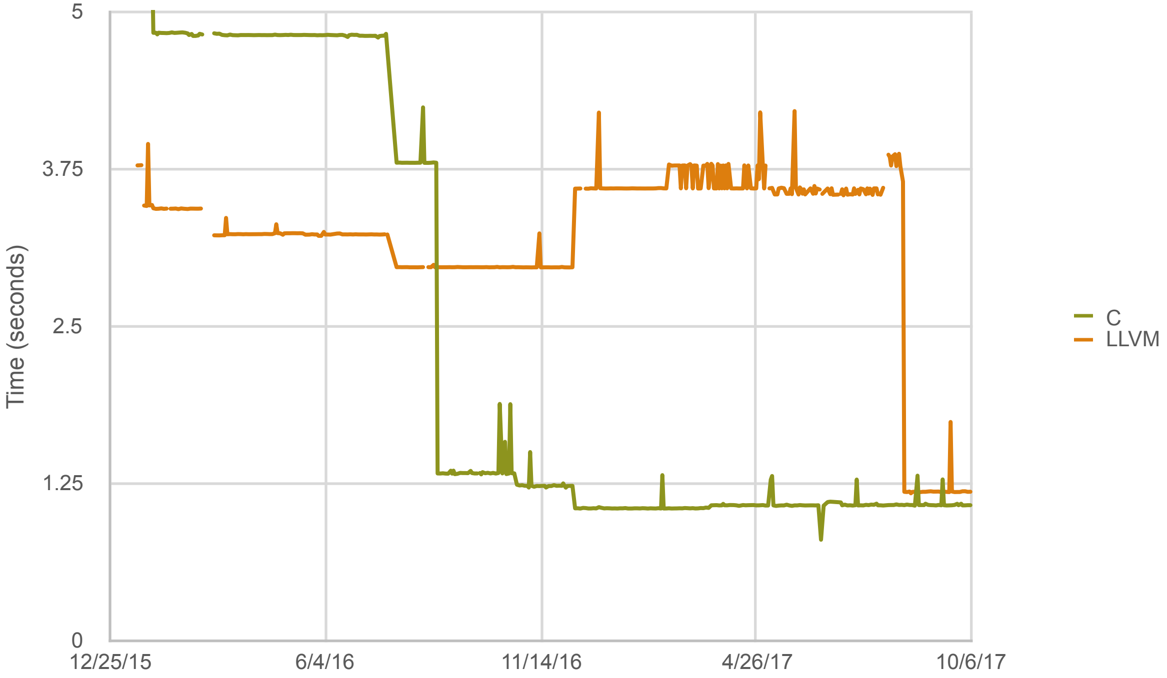


Performance Improvements: GSoC nsw

PRK stencil got 3x faster with no-signed-wrap on signed integer addition – loop induction variable now identified

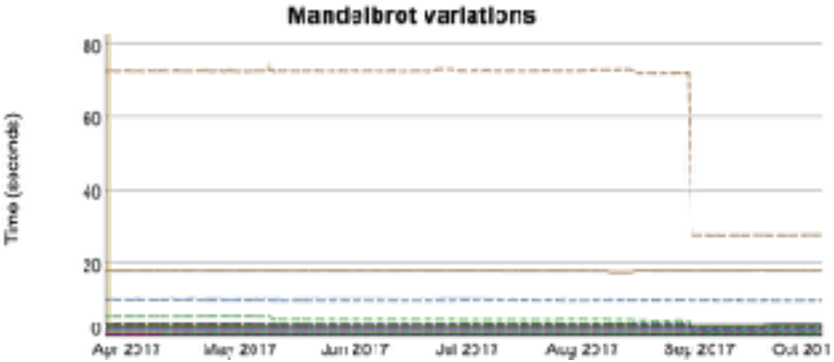
Performance Improvement: GSoC fast float

LCALS fir got 3x faster with LLVM floating point optimizations enabled for --no-ieee-float



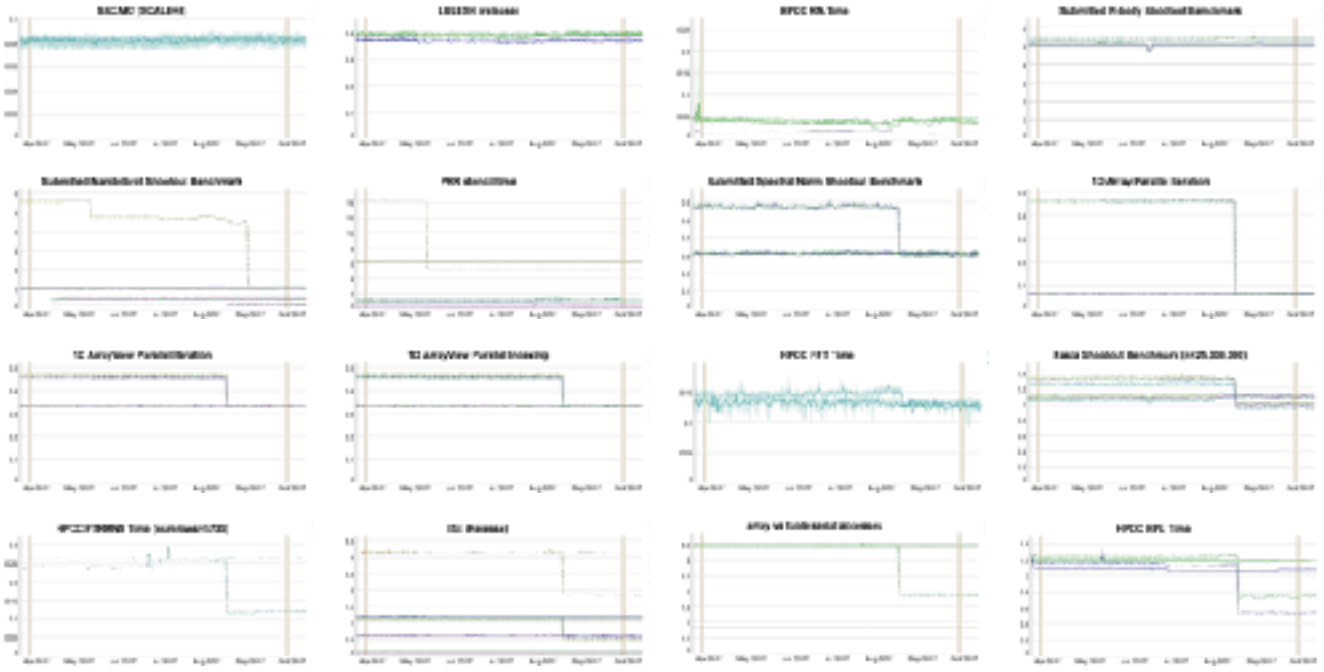
Performance Improvements: Built-ins Header

complex version of Mandelbrot got 3x faster with header implementing clang built-ins



--llvm is Now Competitive

- Benchmark runtime now competitive or better with --llvm



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