Advances in Charm-based Languages (II)

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Outline

1. Context
2. Our Approach
3. Enhancements
4. Results
5. Future Work
6. Conclusions

Why DSLs?

Hardware complexity continues to rise, posing challenges in:

- Programming heterogenous systems
- Updating specialized software for new hardware
- Choosing the best hardware configuration

In response to these challenges, we need:

- Better tools (e.g., auto-tuners) for navigating problem spaces
- Lift the abstraction level away from hardware complexities
- Languages better suited for HPC than C/C++ and Fortran

Domain-specific languages (DSLs) can help address these needs

DSLs in HPC

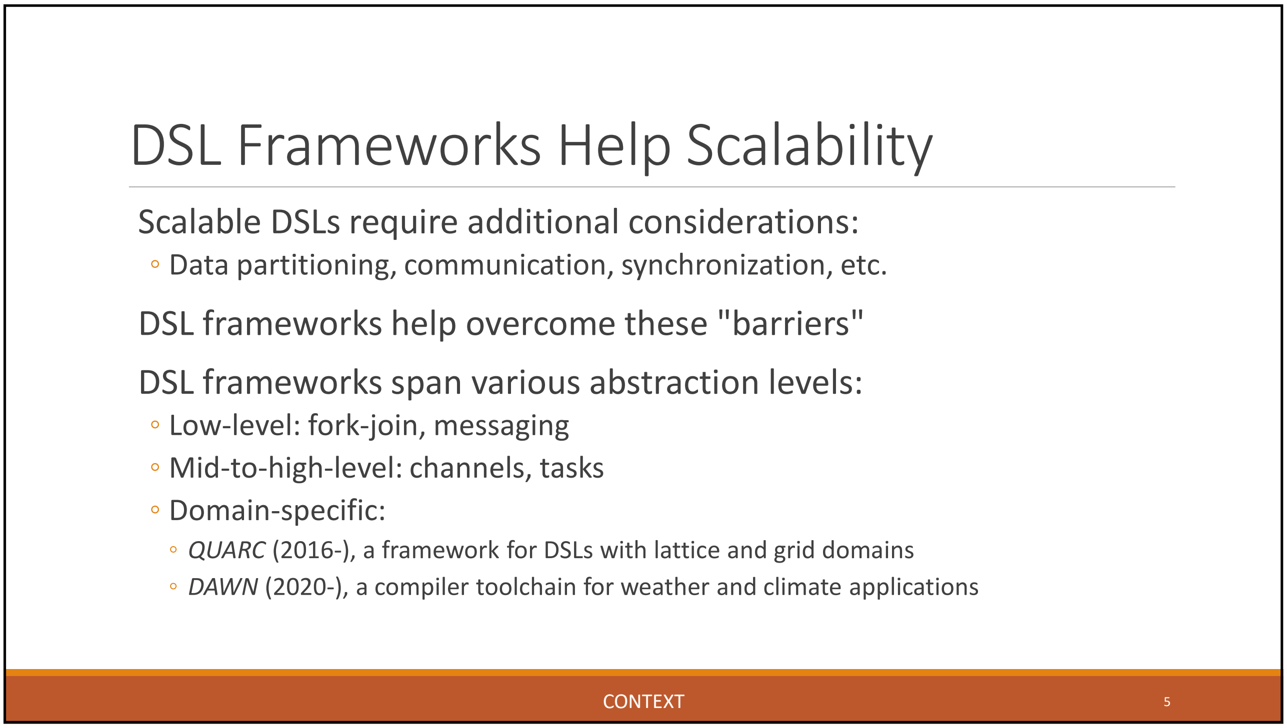
DSLs integrate domain knowledge to enhance:

- *Productivity* – direct access to common abstractions
- *Efficiency* – smaller search space that tools "know" how to navigate

Research in HPC supports distributed DSLs:

◦ *PyOP2* (2012-)	mesh-based codes, embedded in Python
◦ *GridTools* (2016-)	stencil computations, embedded in C++
◦ *OpenPME* (2017-)	particle and mesh methods, standalone

However, DSLs that scale beyond a single node are rare!



DSL Frameworks Help Scalability

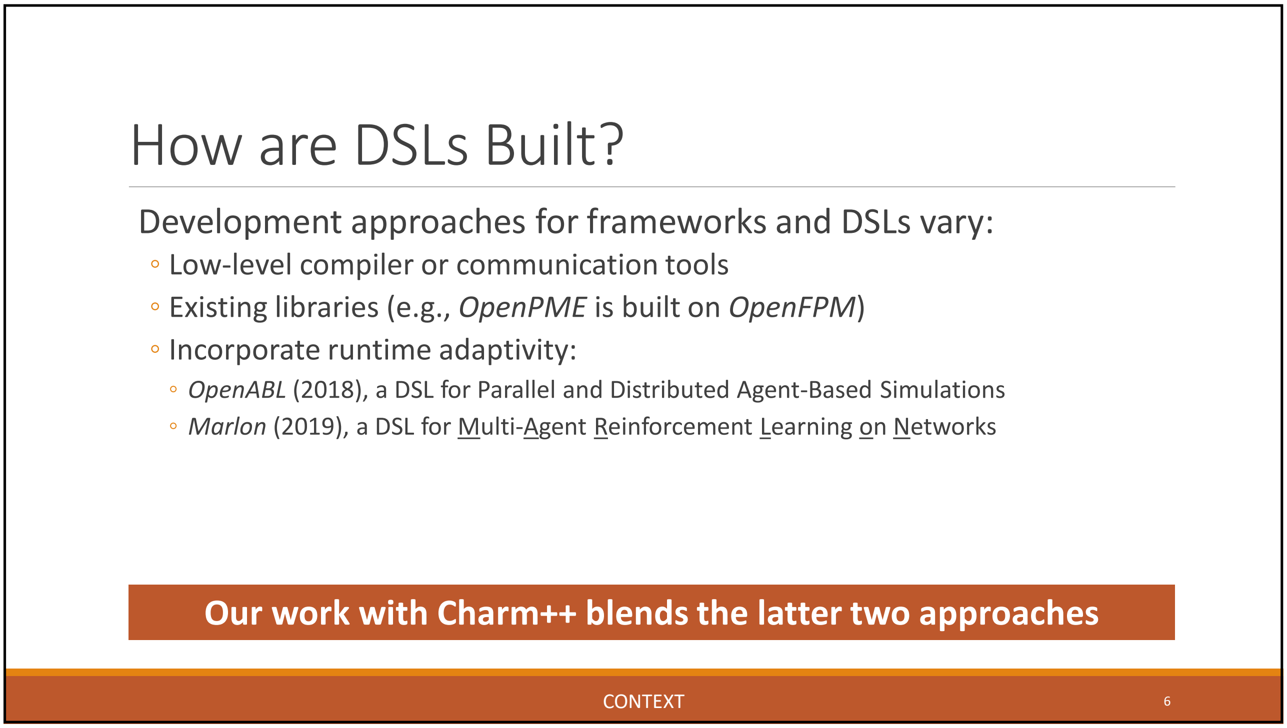
Scalable DSLs require additional considerations:

- Data partitioning, communication, synchronization, etc.

DSL frameworks help overcome these "barriers"

DSL frameworks span various abstraction levels:

- Low-level: fork-join, messaging
- Mid-to-high-level: channels, tasks
- Domain-specific:
  - *QUARC* (2016-), a framework for DSLs with lattice and grid domains
  - *DAWN* (2020-), a compiler toolchain for weather and climate applications



How are DSLs Built?

Development approaches for frameworks and DSLs vary:

- Low-level compiler or communication tools
- Existing libraries (e.g., *OpenPME* is built on *OpenFPM*)
- Incorporate runtime adaptivity:
  - *OpenABL* (2018), a DSL for Parallel and Distributed Agent-Based Simulations
  - *Marlon* (2019), a DSL for Multi-Agent Reinforcement Learning on Networks

Our work with Charm++ blends the latter two approaches

What Charm++ Offers DSLs

Charm’s migratable objects have worthwhile properties for DSLs:

- Intrinsic over-decomposition and runtime adaptivity
- Flexible local view of control and data

Noting these benefits, past Charm-based works built:

- Parallel abstractions: Trees, Futures, PGAS-like Structures (i.e., MSA)
- DSLs: Charisma, DivCon

**These DSLs did not leverage a framework:
repetitive to develop, harder to maintain**

Migratable Objects Pose Challenges

Migratable objects require rich OOP support, but DSL frameworks:

- Often leave classes and generic types as “exercises”
- Performance suffers without first-class support

Embedding migratable objects in……

C++

- Lacking standards
- STL containers force copying
- Syntactic constraints cause verbosity

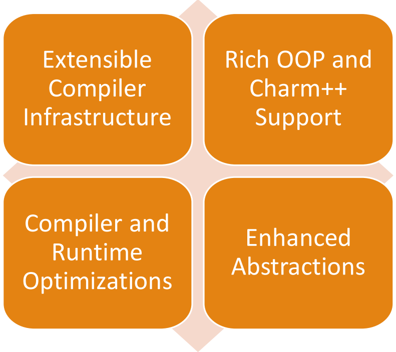
Interpreted or JIT'd languages

- Harms performance
- Although Python and the JVM have improved for some domains

Our Approach

EÍR: A compiler framework to build DSLs based on Charm++

- Extensible compiler supports DSL analysis and transformation passes
- Rich support for OOP and Charm++:
  - Automatically registers and de/serializes user-defined types
- C++ backend with runtime and compiler-level communication optimizations
- Enhanced runtime-level support for performance-critical abstractions



Our Goals

To prove and drive the generality of *EÍR*:

- We built a Scala-inspired, general-purpose language with *EÍR*
- Embedded DSLs within it, like *Charisma* (for data-independent data-flows)

Beyond this, we have explored:

- Elevate visibility of internal mechanisms when:
  - Useful for constructing other parallel abstractions
  - Avoidable performance impact
- Facilitate optimizations through stronger guarantees:
  - Discourage user-level locks, regulate data-sharing, etc.
- Extend the underlying model to minimize "semantic gaps."

Eliminating Tedium

Charm++

```
...
template<typename T> entry void print(T t);
...
// need to register all specializations
extern entry void printer print<std::string>(std::string);
extern entry void printer print<double>(double);
...
```

EÍR

```
...
@entry def print<A>(a: A);
...
printerProxy.print(“hi!”);   // no registration
printerProxy.print(42.0);    // necessary
...
```

De/serialization Optimizations

Identity aware/finer-graph packing

- Effortlessly handles recurrent relationships (doubly-linked graphs)
- Each unique object is packed only once
- Back-references are used for duplicates

Global pointer-to-offset optimizations

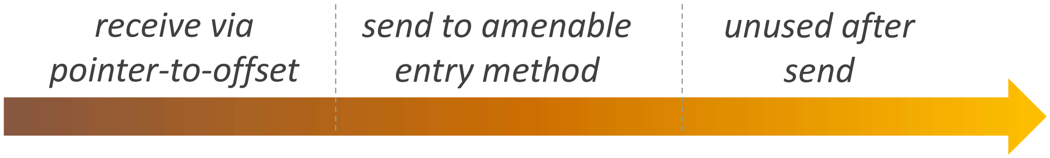
- Deserialize POD-types as pointers to an offset within a message buffer
- Retains ownership of the message with a reference-counted pointer
- **No overhead for encapsulation**
- Charm++ requires an extra copy

```
struct array_holder {
    val arr: array<double>;
    ...
```

In-place message optimizations

- Edit a retained message **“in-place”** then resend it (e.g., arrays)
- EIR uses a control-flow analysis pass to find “repacking” opportunities

What are in-place optimization opportunities?



receive via pointer-to-offset

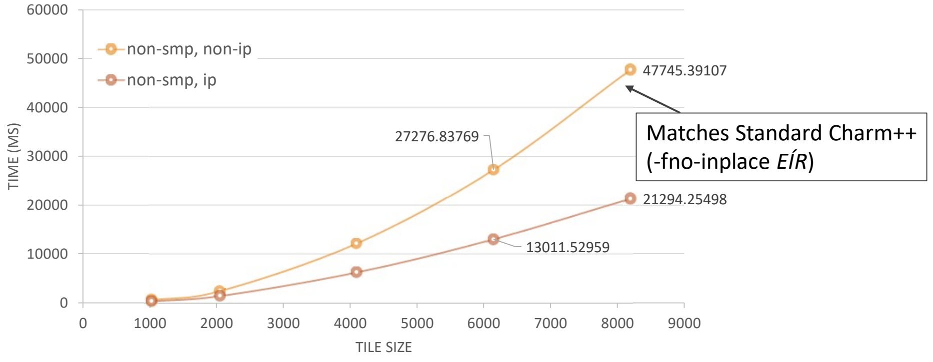
send to amenable entry method

unused after send

```
@overlap for (var block = 0; block < nBlocks; block += 1) {
    when inputA(_ == block, blockA: array<double, 2>),
         inputB(_ == block, blockB: array<double, 2>) => {
        ...
        if (...) {
            self@[...].inputA(block + 1, blockA);
            self@[...].inputB(block + 1, blockB);
        }
    }
}
```

Effects of In-Place Optimizations

EÍR, Cannon's Matmul, Comm-Only
(4 Physical Nodes, 169PEs)



Matches Standard Charm++ (-fno-inplace *EÍR*)

SDAG (Structured Dagger)

SDAG is used to represent parallel control flow in **Charm++**

- Expresses the dependencies between messages and local control flow
- Can direct progress through phases of a computation

```
for (it = 0; it < numIts; it += 1) {
    serial { update_neighbors(...); }
    for (imsg = 0; imsg < numNeighbors; imsg += 1) {
        when recv_update(...) { ... }
    }
    serial { check_and_compute(...); }
    if (it != (numIts - 1)) {
        when recv_iter_summary(...) { ... }
    }
}
when recv_total_summary(...) { ... }
```

Extending SDAG with Mailboxes

Mailboxes enable Erlang-like *selective receives*:

- Blend pattern matching and message processing (rich predicates!)
- SDAG, only one reference number per “when” clause

```
entry void receive(CMK_REFNUM_TYPE);

entry void run(int nIters) {
   serial { this->send(nIters); }
   forall [i] (0:(nIters - 1),1) {
      forall [j] (0:(CkNumPes() - 1),1) {
         when receive [join(i, j)] (CMK_REFNUM_TYPE) {}
      }
   }
}
```

[0-255] Range

```
@mailbox def receive(it: int, pe: int);

@threaded @entry def run(numIters: int) {
   self.send(numIters);
   @overlap for (var i = 0; i < numIters; i += 1) {
      @overlap for (var j = 0; j < ck::numPes(); j += 1) {
         when receive(_ == i, _ == j) => ();
      }
   }
}
```

Unconstrained

Example Pattern Matching

```
trait response<T> { ...}
class pong with response<string> {...}
class ping with response<string> {...}


@mailbox def receive(src: int, msg: response<string>);

@threaded @entry def exchange() {
    @overlap for (var it = 0; it < ck::numPes(); it += 1) {
        await all {
            when receive(src, msg: ping) if src == it => { ... }
            when receive(src, msg: pong) if src == it => acknowledge(src, msg);
        }
    }
    self[@]contribute(...);
}
```

Only matches ping/pong

Other Mailbox Features

Compound Clauses	`when foo(…), bar(…) => { … }`

Await All	`await all {`
	`when foo(…) => {…}`
	`when bar(…) => {… when baz(…) => {…}}`
	`}`

“Overlapped” Execution	Only the ordering of ***baz*** after ***bar*** is enforced, ***foo*** can execute between or after them.

Sections

Sections facilitate efficient operations over subsets of collectives

Their current Charm++ API is constrained:

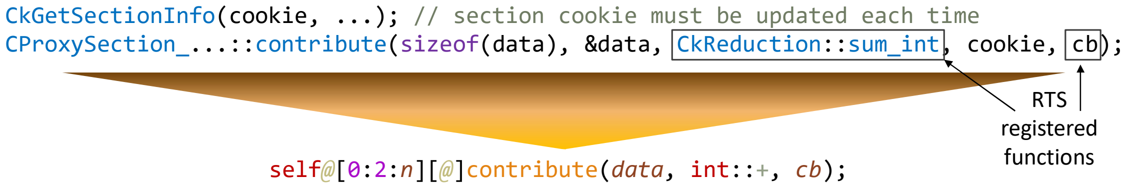
- Explicit, centralized creation
- User-managed “cookies” for correctness

Work is underway to improve sections in Charm++,

- Integrating innovations from Charm4py:
  - Elimination of “cookies”
  - Distributed section creation

compiler support can help too!

Sections (cont.)



```
CkGetSectionInfo(cookie, ...); // section cookie must be updated each time
CProxySection_...::contribute(sizeof(data), &data, CkReduction::sum_int, cookie, cb);
```

```
self@[0:2:n][@]contribute(data, int::+, cb);
```

Goals

- Eliminate section registration, “create” sections at the call-site
- Statically-typed callbacks and combiner function
- Enable using lambda functions for these parameters:

```
self[@]contribute(..., (i, j) => ..., i => println(`the result was $i!`));
```

Other Features of *EÍR*

Rich support for generic types,
- Support for parameter packs and tuple manipulation
- Swift-like “where” clauses to enforce constraints on generics
- Like “std::enable_if” or “requires” in C++20 (i.e., SFINAE)

Operator overloading,
- Objects can be used as “functors”
- Arbitrary identifiers for infix operators (ranges by “1 **to** n”)

Pattern matching,
- User-defined “extractor” methods (like Scala)
- Optional values can be matched with:
  “case some(x) => …” or “case none() =>”

Other Features of *EÍR* (cont.)

Features woven together to form a rich STL that…
- Also includes parallel abstractions:
  - Distributed Hash Tables and Tuple Spaces
  - Channels
  - Futures

Written various mini-apps:
- Jacobi’s method in 2D
- Cannon’s matrix-matrix multiplication

Results (cont.)

Performance typically matches or exceeds Charm++:

- Gains usually in the 5~20% range...
- *Unless* larger optimizations are involved (e.g., Cannon’s)
- Complexities in message delivery preclude larger gains
- Required to facilitate mailboxes, lightweight sections, etc.

Thus, we have recently focused on micro-benchmarking:

- Roundtrip “ping pong” time
- OSU-style bandwidth

We are “closing the gap” between our infrastructure and Charm++

Future Work

Aside from correcting the issues mentioned…

- Limitations of the C++ backend, microbenchmark performance...

We have many ideas for future work with/on our infrastructure:

- Write more mini-apps: LeanMD, BarnesHut, HPCCG, etc.
- Integrate DSLs from Charm’s “back-catalog” (DivCon and MSA)
- Expose a textual representation for *EÍR*
  - Perhaps an XML-based AST like *Omni*’s XcodeML?
- Ensure *EÍR’s* generated code is robustly migratable
- Provide facilities for using hardware accelerators

Conclusions

EÍR, a compiler framework to build DSLs based on Charm++

- Optimizations for message packing
- Enhanced message processing via mailboxes
- Offers “lightweight” sections

Plan to publish soon – more to say then!

Please reach out if you’re interested!

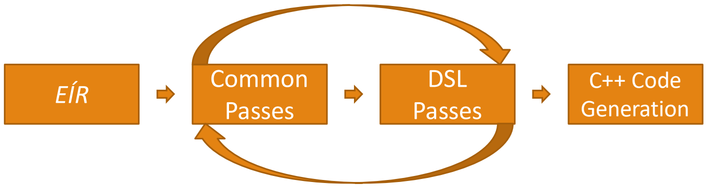
What’s in the Box?

- Lightweight sections…
  - Creation, reductions, and multicasts
- Mailboxes
- Futures
- Aggregations
- Hashing
- De/serialization
- Migratable threading primitives
- And… more!

Code Generation in *EÍR*

Like Charj before it, *EÍR* is written in Scala and targets C++:

- Competitive performance
- Trivializes interoperability with Charm++ libraries



EÍR → Common Passes → DSL Passes → C++ Code Generation

- *EÍR's* C++ backend currently has some limitations (e.g., generics and lambdas) compared to targeting a purpose-built backend (e.g., MLIR)
- However, with additional effort, we can overcome them