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

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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++**

```cpp
template< typename T > entry void print(T t);

extern entry void printer print<std::string>(std::string);
extern entry void printer print<double>(double);

@entry def print<A>(a: A);

printerProxy.print("hi!");  // no registration
printerProxy.print(42.0);    // necessary
```

**EIR**

```
... // need to register all specializations
```

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

- **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

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

ENHANCEMENTS

11

ENHANCEMENTS

12
What are in-place optimization opportunities?

**receive via**
[pointer-to-offset]

**send to amenable**
[entry method]

**unused after**
[send]

```java
@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

**EIR**, Cannon’s Matmul, Comm-Only
(4 Physical Nodes, 169PEs)

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

```plaintext
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(...) { ... }
}
```

**ENHANCEMENTS**

**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

```plaintext
entry void receive(CMK_REFNUM_TYPE);

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

```plaintext
@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) => ();
        }
    }
}
```

[0-255] Range

Unconstrained
Example Pattern Matching

```scala
trait response[T] { ... }

class pong with response[String] {...}
class ping with response[String] {...}
```

```scala
@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: pong) 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**
  ```scala```
  ```scala
  when foo(...), bar(...) => { ... }
  ```

- **Await All**
  ```scala```
  ```scala
  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!

ENHANCEMENTS

Sections (cont.)

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")`;

Goals
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 EIR
  - Perhaps an XML-based AST like Omni’s XcodeML?
- Ensure EIR’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'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