Towards a cross-platform, polyglot implementation of *Aggregate Computing* in ScaFi3

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Motivations

- Aggregate Computing (AC) reference scenario: swarm robotics and large-scale pervasive environments (wearables, smartphones).
- Several implementations of AC exist for different programming languages to:
  - target different platforms and environments;
  - leverage unique strengths of the host programming languages;

However:

- Each of these were developed from scratch, with no code reuse and compatibility in mind;
- No common framework led to AC ecosystem fragmentation.

Goal

Investigate the feasibility of building a framework capable of targeting multiple platforms while offering interoperability with other languages.

$\Rightarrow$ *Scala 3* is perfectly suited for implementing AC abstractions and models in a strongly typed internal DSL.

Scala 3 cross-platform capabilities

Primary target: **JVM** (desktop, server, Android) & *Java* interop;

Target	Supported environment	Language interop	Ecosystem maturity	Toolchain maturity
JavaScript	browser, Node.js, WebAssembly*	*JS* via annotations, *TypeScript* indirectly	Mature	Mature
Native	x86-64, aarch64, 32-bit architectures*	*C*	Growing	Developing

Note: Scala Native cannot target microcontrollers! SoC like *Raspberry Pi* are supported instead.

* Experimental support

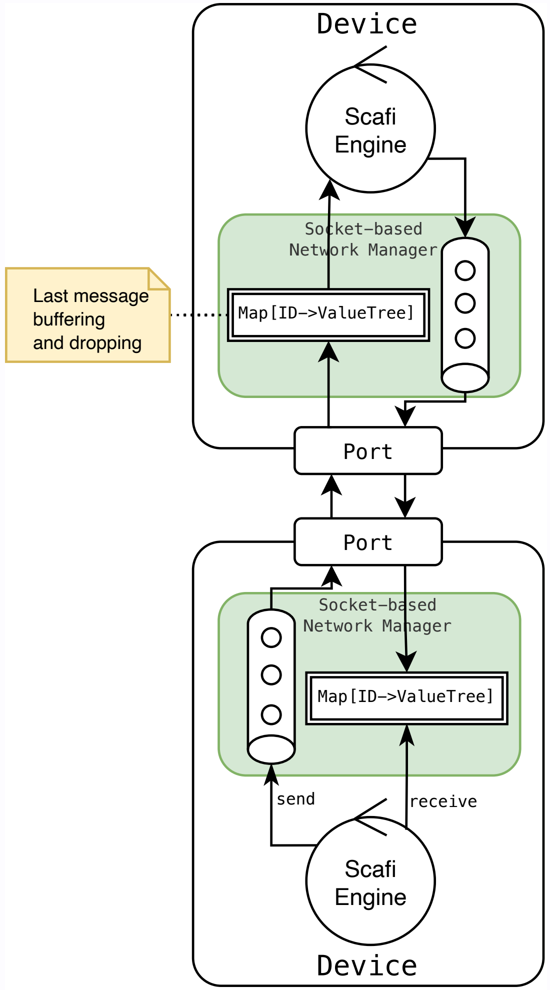
Contribution

The contribution of this thesis span three main axes:

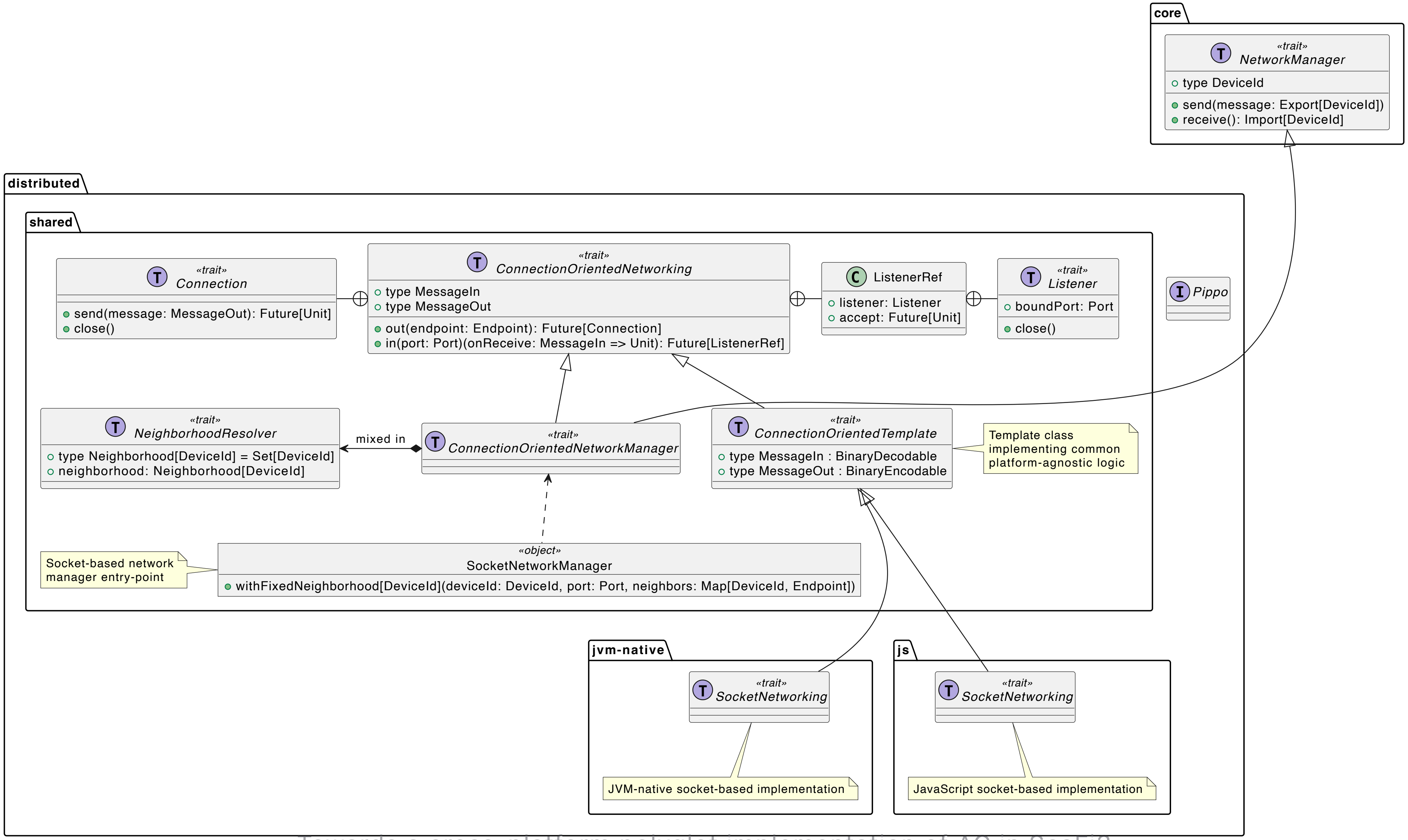
1. **Add a cross-platform *distribution* module;**
2. Add support for a general *cross-platform* and *polyglot* serialization binding;
3. Add a *cross-platform*, *polyglot* library abstraction layer.

Cross-platform distribution module

- Technology: *stream*, *TCP*-based *connection-oriented sockets*;
    - Each device is bound to a specific *endpoint* (IP + port);
    - Point-to-point connections between neighbors;
    - Neighborhood is statically *fixed* at initialization but can be extended in the future with dynamic discovery strategies;
- Support for multiple platforms: *JVM*, *JS* (Node.js), *Native*;
    - *JVM* + *Native* support via Java Standard *sockets* library;
    - *JS* support via *Node.js net* module using Scala.js type facades;
    - **Implications**:
        - shared code cannot perform blocking operations;
        - all the API is designed to be asynchronous and non-blocking;
        - primary goal: write as much shared code as possible, minimizing platform-specific implementations.



Simplified class diagram of the socket-based distribution module:



An example of Scala.js facade over the Node.js `Net` class to allow interoperability with Node.js networking APIs:

```scala
@js.native
@JSImport("net", JSImport.Namespace)
object Net extends js.Object:

  /** A factory function which creates a new Socket connection. */
  def connect(port: Int, host: String): Socket = js.native

  /** A factory function which creates a new TCP or IPC server. */
  def createServer(connectionListener: js.Function1[Socket, Unit]): Server = js.native
```

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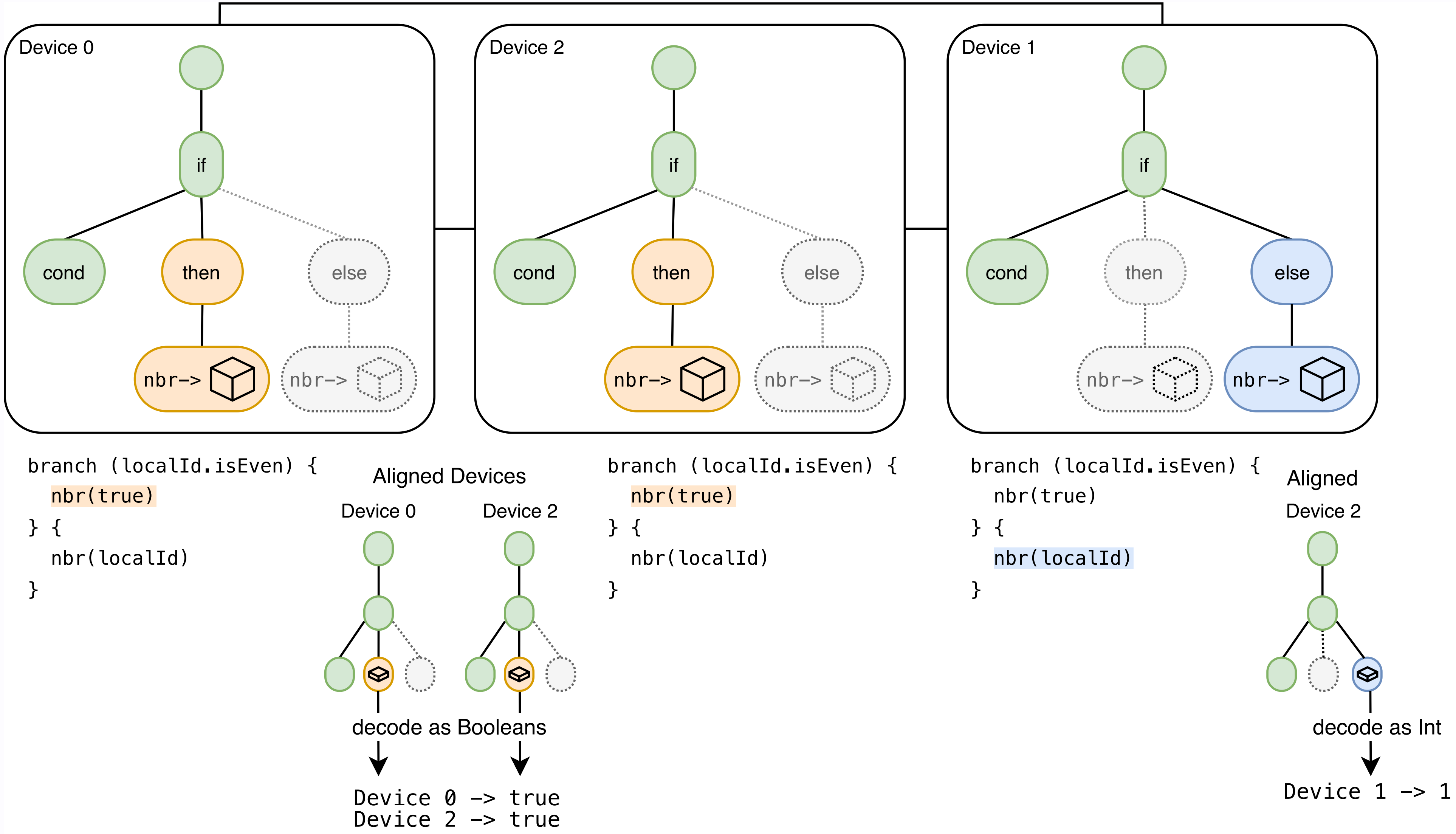
Serialization binding



- Devices exchange (ID, Value Tree) pairs;
- When exchanging data, values are inserted into the Value Tree encoded using a specific serialization format
  - This is possible since, in the context of an `exchange`, the type information of the value is known
- When receiving data, the Value Tree is decoded but values remain encoded in their serialized format
- Only when the corresponding exchange in the aggregate program is evaluated the value is decoded
  - Again, this is possible since the type information of the expected value is known at that point
- Technically, this is achieved via a combination of Scala 3 *type classes* and *type lambdas* that abstract over the serialization format and allow to cleanly express encoding and decoding requirements as *type bounds*.

- Encodable and Decodable type classes for encoding and decoding generic messages from/to a format (e.g., JSON, binary, ...)

```scala
/** A type class for encoding messages. */
trait Encodable[-From, +To]:

  /** @return the encoded value in the target type. */
  def encode(value: From): To

/** A type class for decoding messages. */
trait Decodable[-From, +To]:

  /** @return the decoded data in the target type. */
  def decode(data: From): To

/** A type class for encoding and decoding messages. */
trait Codable[Message, Format] extends Encodable[Message, Format] with Decodable[Format, Message]

// Type alias for express encodable and decodable capabilities as type bound on values

type EncodableTo[Format] = [Message] =>> Encodable[Message, Format]

type DecodableFrom[Format] = [Message] =>> Decodable[Format, Message]

type CodableFromTo[Format] = [Message] =>> Codable[Message, Format]
```

Every function dealing with, possibly, values distribution add as type bound a Codable instance

```
// inside this function body, Values can be both encoded and decoded
override def xc[Format, Value: CodableFromTo[Format]](
  init: SharedData[Value],
)(
  f: SharedData[Value] => (SharedData[Value], SharedData[Value]),
): SharedData[Value] =
  alignmentScope("exchange"): () =>
    val messages = alignedMessages.map { case (id, value) => id -> value }
    val field = Field(init(localId), messages)
    val (ret, send) = f(field)
    writeValue(send.default, send.alignedValues)
    ret

// extracts the aligned values from the Value Tree and decode them using contextually
// available decoder for Value
def alignedMessages[Format, Value: DecodableFrom[Format]]: Map[DeviceId, Value] = ...

// add a new value into the Value Tree that will be sent to neighbors already serialized using
// contextually available encoder for Value
def writeValue[Format, Value: EncodableTo[Format]](default: Value, overrides: Map[DeviceId, Value]): Unit =
  ...
```

- In non-distribution scenarios, like simulation or local testing, encoding and decoding is a no-op:

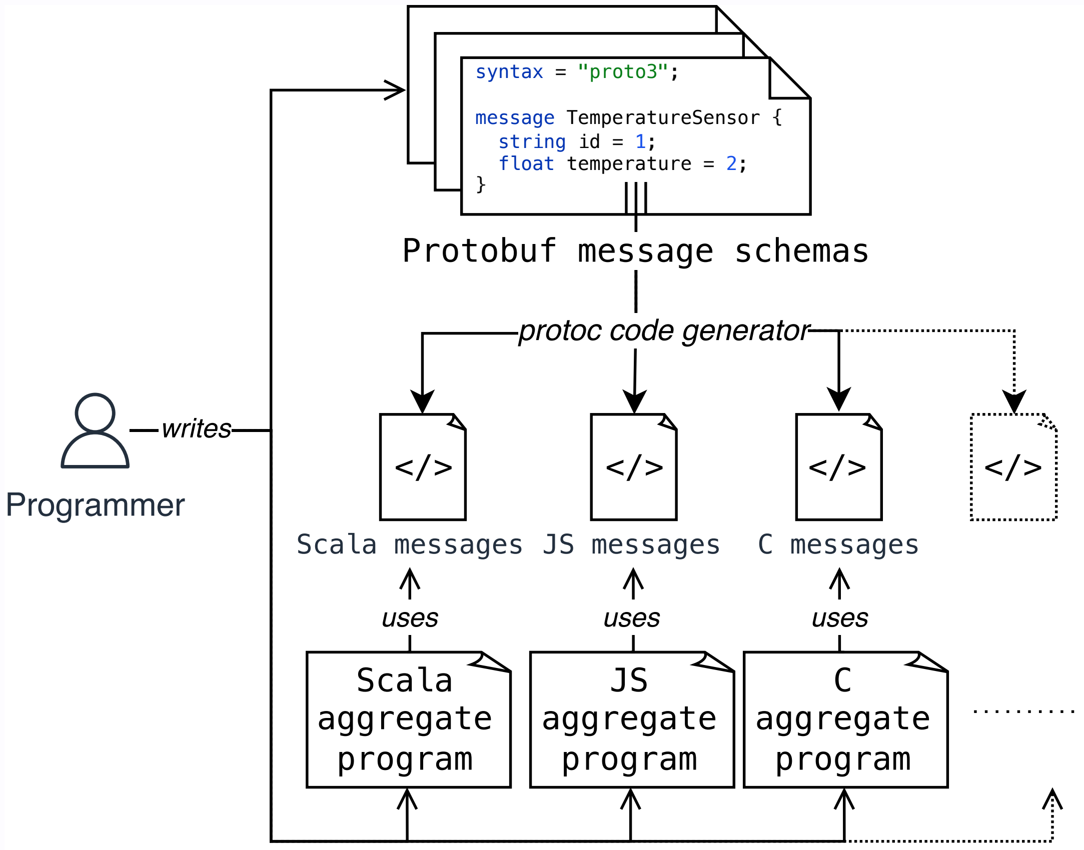
```scala
given forInMemoryCommunications[Message]: Codable[Message, Message] with
  inline def encode(msg: Message): Message = msg
  inline def decode(msg: Message): Message = msg
```

- Useful for API using exchange primitive only for state evolution, like `evolve`, where we do not want to force users to provide encoders/decoders for their values:
  - network managers needs to be implemented to ignore any non-Format values

```scala
override def evolve[Value](initial: Value)(evolution: Value => Value): Value =
  // `exchange` is called only to update the self-value: `None` is shared with neighbors, so an in-memory
  // codec is enough; non-in-memory network managers will ignore it since it is not serialized.
  exchange(None)(nones =>
    val previousValue = nones(localId).getOrElse(initial)
    nones.set(localId, Some(evolution(previousValue))),
  )(using Codables.forInMemoryCommunications)(localId).get
```

Polyglot serialization format

- Aggregate programs interoperability depends on common serialization formats
  - if formats are not compatible, values decoding fails;
- Cross-language interoperability is achieved via common serialization formats
  - Different languages have different abstractions: data classes/structures in one language may not have direct equivalents in another;
  - Manual serialization in a common format can be error-prone and tedious;
- ***Protobuf*** **as language- and platform-agnostic serialization library**
  - generates code for multiple languages from a single schema definition, including Scala, Python, Java, C, C++, JS, TS, Go, Rust, ...



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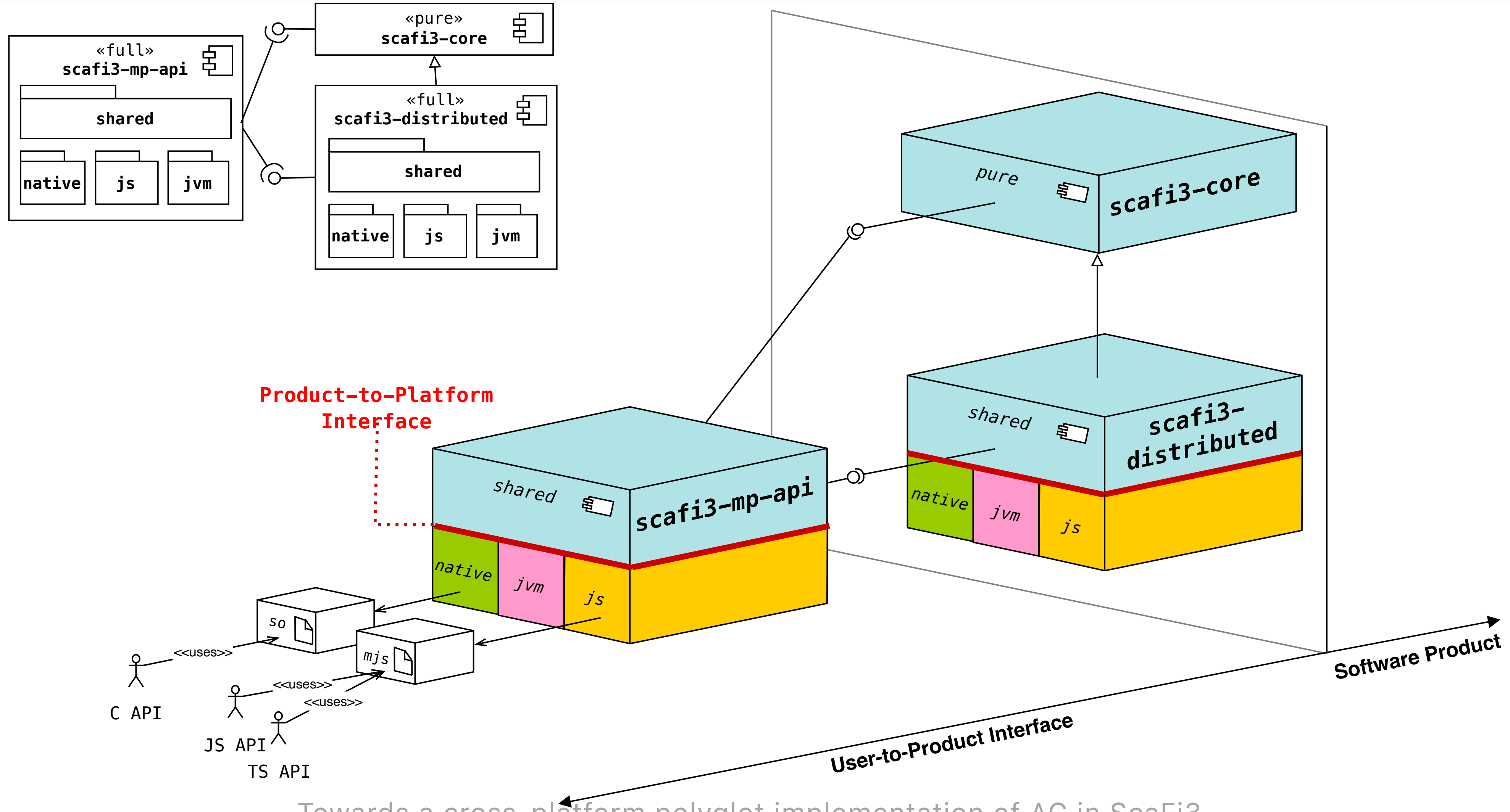
Architecture

The `scafi3-mp-api` module serves as the **User-to-Product Interface**, *exposing* the Scafi API to multiple languages.



- Currently, C and JavaScript are the two reference languages for, respectively, Native and JS targets;
- API exposure is achieved via annotation;

Problems:

- both Scala Native and Scala.js deals with language semantics mismatch reifying them in the type system with specific types.
- only a subset of Scala type constructs can be mapped and exposed to other languages
  - the fact a Scala 3 construct can be cross-compiled to other platforms doesn't imply it can be exposed to other languages;

Proposed solution:

- in order to write a unified wrapper API that can be exported, an abstraction layer is used. Their goals are:
  - create abstract language-independent types, leaving their implementation and mapping to Scala 3 types to the specific platform module;
  - expose to other languages a simplified version of the ScaFi3 API containing only constructs that can be mapped and implement it as a thin wrapper that internally decodes/encodes values to/from the abstract types delegating all the logic to ScaFi3.

An isomorphism type class to express a dual conversion between abstract portable types and Scala types:

```scala
/** An isomorphism between two types `A` and `B`. */
trait Iso[A, B]:
  def to(a: A): B
  def from(b: B): A

object Iso:
  given [A, B](using iso: Iso[A, B]): Conversion[A, B] with
    inline def apply(a: A): B = iso.to(a)

  given [A, B](using iso: Iso[A, B]): Conversion[B, A] with
    inline def apply(b: B): A = iso.from(b)
```

Polyglot abstract independent types:

```scala
trait PortableTypes:

  /** A portable Map that can be used across different lang. */
  type Map[K, V]

  /** Portable maps are isomorphic to Scala's `collection.Map`. */
  given [K, V] => Iso[Map[K, V], collection.Map[K, V]] =
    compiletime.deferred

  /** Portable 0-arg function type that can be used across lang. */
  type Function0[R]

  /** Portable 0-arg function can be converted to Scala's `() => R`. */
  given toScalaFunction0[R]: Conversion[Function0[R], () => R]

  // ... all the other portable types needed by the wrapper API ...
```

On *Native*:

```scala
trait NativeTypes extends PortableTypes:

  // maps are exposed as void* pointers in C
  override type Map[K, V] = Ptr[Byte]
  override given [K, V] => Iso[Map[K, V], collection.Map[K, V]] =
    Iso(CMap.of(_).toMap, m => CMap(mutable.Map.from(m)))

  // A function pointer R (*f)() in C
  override type Function0[R] = CFuncPtr0[R]
  given toScalaFunction0[R]: Conversion[Function0[R], () => R] with
    inline def apply(f: Function0[R]): () => R = f.apply

  // ... all the other portable types needed by the wrapper API ...
```

On *JS*:

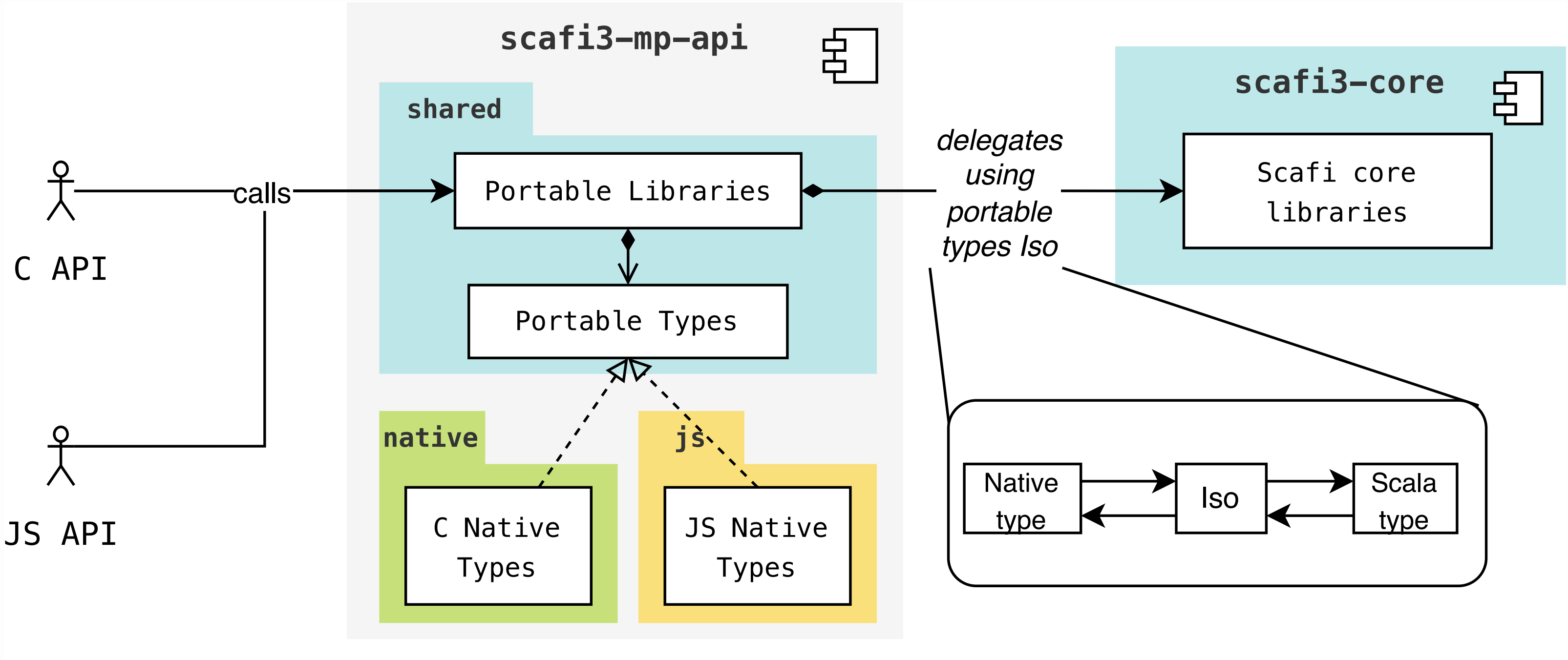
```scala
trait JSTypes extends PortableTypes:

  // maps are exposed as js.Map in JavaScript
  override type Map[K, V] = js.Map[K, V]
  override given [K, V] => Iso[Map[K, V], collection.Map[K, V]] =
    Iso(_.toMap, m => js.Map(m.toSeq*))

  // A JavaScript function () => R
  override type Function0[R] = js.Function0[R]
  given toScalaFunction0[R]: Conversion[Function0[R], () => R] with
    inline def apply(f: Function0[R]): () => R = f.apply

  // ... all the other portable types needed by the wrapper API ...
```

- Wrapper API is written as a thin layer over ScaFi3 using only portable types
- all the logic is delegated to ScaFi3 after converting portable types to Scala types using the provided isomorphisms and implicit conversions



```scala
trait PortableLibrary:
  self: PortableTypes => // requires PortableTypes
  export it.unibo.scafi.language.AggregateFoundation

  /** The language type comprising all the needed syntaxes needed to implement the library functionalities. */
  type Language <: AggregateFoundation

  /** The [[Language]] instance used by the library to which delegate the syntax operations. */
  val language: Language

  /** A portable, semantically equivalent definition of the [[language.SharedData]] data structure. */
  type SharedData[Value]

  /** [[SharedData]] is isomorphic to [[language.SharedData]]. */
  given [Value]: Iso[SharedData[Value], language.SharedData[Value]] = compiletime.deferred

trait PortableExchangeCalculusLibrary extends PortableLibrary:
  self: PortableTypes =>
  export it.unibo.scafi.language.xc.syntax.ReturnSending as RetSend

  // requires ExchangeSyntax to delegate exchange implementation
  override type Language <: AggregateFoundation & ExchangeSyntax

  /** A portable, semantically equivalent definition of the [[language.RetSend]] data structure. */
  type ReturnSending

  given [Value] => Conversion[ReturnSending, RetSend[language.SharedData[Value]]] =
    compiletime.deferred

  @JSExport
  def exchange[Value](initial: SharedData[Value])(
    f: Function1[SharedData[Value], ReturnSending]
  ): SharedData[Value] =
    // Thanks to the Iso in scope the wrapper implementation is just delegation...
    language.exchange(initial)(f(_))
```

Implementation challenges

More specifically the abstraction layer must take into account several challenges:

- every language difference must be modeled as an abstract portable type with its mapping to Scala types;
- difference in semantics of asynchronous computations;
- differences in equality and hashing semantics;
- differences in memory management and resource cleanup.

Pros:

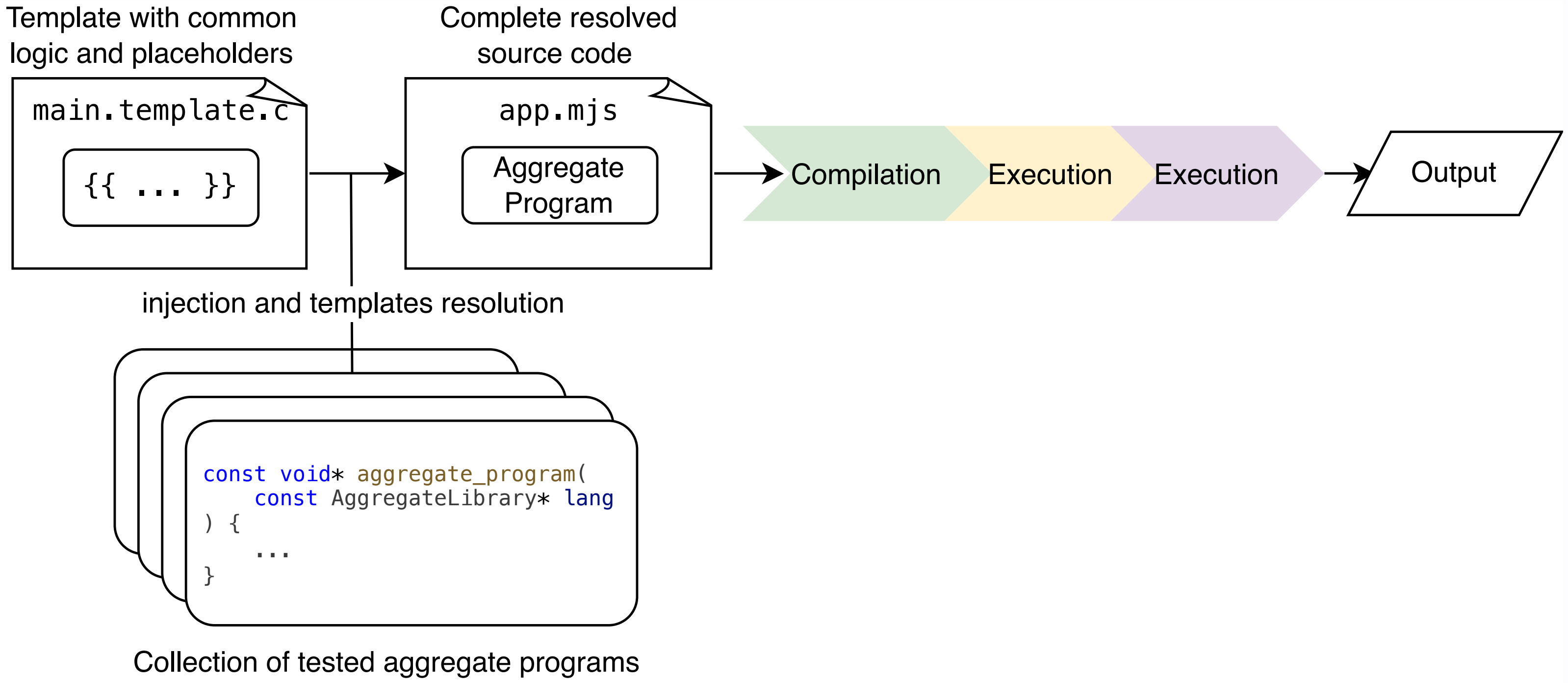
- unified AC model and clean and idiomatic API in Scala 3;
- wrapper implementation is just delegation thanks to isomorphisms and implicit conversions;
- full code reuse across all supported platforms: any change in the core and distributed modules is automatically reflected in all platforms;
- code reuse for polyglot serialization is maximized
    - if new API features are added, they require to be wrapped only once in the portable library layer;
    - though, for Typescript and C manual type definitions must be written, no code generation automatism is provided (possible future work).

Cons:

- ScaFi Native APIs are often untyped where C lacks generics—generic containers and callbacks use `void*`, requiring unsafe casts;
- on native only static objects can be exported. To simulate class-like behavior function pointers as struct fields are used but requires boilerplate code to manually implement method dispatching;
- on native, memory management is manual: heap-allocated structures must provide custom allocation and deallocation methods to avoid memory leaks;
  - this can be mitigated using allocation strategies keeping track of all allocated objects and deallocating them at once at the end of each round;
- on Scala Native and for Typescript no automatism for generating type definitions.
  - Future work: sbt plugin to generate C header files and Typescript definition files from Scala annotated code.

Integration Testing

- tests are run on each platform to ensure correctness and interoperability;
- polyglot API is tested using a simple framework inspired to *snapshots testing*:
  - a template for each supported language is defined containing common logic to setup the environment and run aggregate programs;
  - variable logic and aggregate programs are injected into the template by the testing framework using placeholders (`{{...}}`);
  - once test source code is complete, it is compiled, run and its output compared to the expected one.



Demo: gradient by *hop count*

C implementation:

```c
float min(Array* nvalues) {
    float min_distance = FLT_MAX;
    for (size_t i = 0; i < nvalues->size; i++) {
        const ProtobufValue* d = nvalues->items[i];
        float neighbor_dist = ((const Distance*)d->message)->value;
        min_distance = neighbor_dist < min_distance ? neighbor_dist : min_distance;
    }
    Array_destroy(nvalues);
    return min_distance;
}

const void* aggregate_program(const AggregateLibrary* lang) {
    return lang->share(distance_of(FLT_MAX), fn(const BinaryCodable*, (const Field* f), {
        float min_distance = min(without_self(f));
        free(f);
        return is_source ? distance_of(0.0) : distance_of(min_distance + 1.0);
    }));
}
```

Scala implementation:

```scala
given Ordering[Distance] = (x, y) => x.value.compare(y.value)

given UpperBounded[Distance] = new UpperBounded[Distance]:
  override def upperBound: Distance = Distance(Float.MaxValue)

def aggregateProgram(using Lang): Distance =
  share(Distance(Float.MaxValue)): nvalues =>
    val minDistance = nvalues.withoutSelf.min.value
    if isSource then Distance(0) else Distance(minDistance + 1.0)
```

Typescript/JS implementation:

```typescript
function aggregateProgram(lang: Language) {
    return lang.share(distanceOf(Infinity), (nvalues) => {
        const minDistance = nvalues.withoutSelf()
            .map((dist) => dist.value)
            .reduce((min, d) => Math.min(min, d), Infinity);
        return isSource ? distanceOf(0) : distanceOf(minDistance + 1.0);
    });
}
```