Selected Challenges in Concurrent and Distributed Programming

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Joint work with Heather Miller, Normen Müller, Xin Zhao, Dominik Helm, Florian Kübler, Jan Thomas Kölzer, Michael Eichberg, Guido Salvaneschi and Mira Mezini

Workshop on Programming Languages and Distributed Systems

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RISE Computer Science, Electrum Kista, Stockholm, Sweden

Goals

- Programming languages for distributed systems that provide high scalability, reliability, and availability
- Prevent bugs in distributed systems

Challenge 1: Ensuring Fault-Tolerance Properties

- Specific fault-tolerance mechanism:
  Lineage-based fault recovery
  - Lineage records dataset identifier plus transformations
  - Maintaining lineage information in available, replicated storage enables recovering from replica faults
- ***A widely-used fault-recovery mechanism*** (e.g., Apache Spark)

How to *statically* ensure fault-tolerance properties for languages based on lineage-based fault recovery?

Programming Model for Lineage-based Distributed Computation

- ***A programming model***
  - for ***functional processing of distributed data***,
  - which provides abstractions for building fault-tolerant distributed systems,
  - including ***first-class lineages*** and ***futures***.
- ***Complete formalization***
  - As an extension of typed lambda-calculus,
  - with futures and distributable closures ("spores"),
  - based on an ***asynchronous, distributed operational semantics***

Programming Model Illustrated

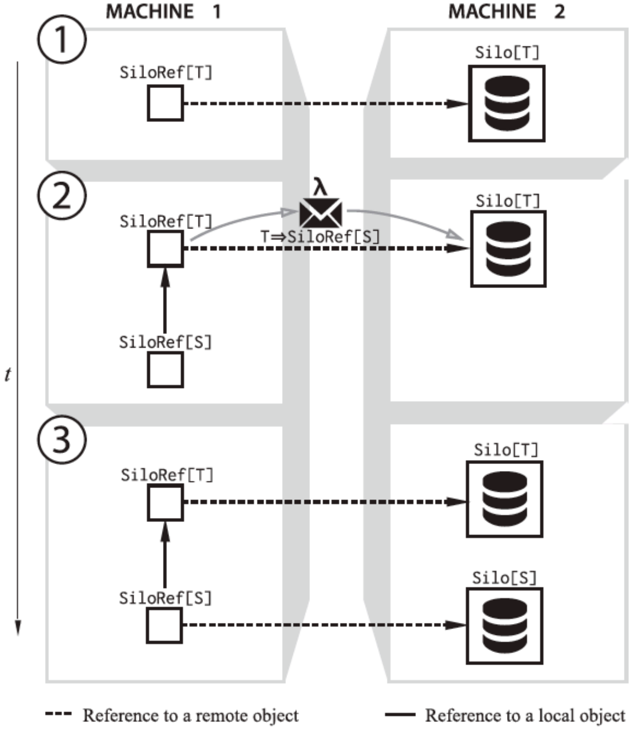

Fig. 1. Basic function passing model.

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Silos

What are they?

Two parts.

- **SiloRef.** Handle to a Silo.
- **Silo.** Typed, stationary data container.

User interacts with SiloRef.

SiloRefs come with 4 primitive operations.

Silos

What are they?

Primitive: apply

```
def apply[S](fun: T => SiloRef[S]): SiloRef[S]
```

- Takes a function that is to be applied to the data in the silo associated with the SiloRef.
- Creates new silo to contain the data that the user-defined function returns; evaluation is *deferred*

Deferred

Enables interesting computation DAGs

Silos

What are they?

Primitive: send

```
def send(): Future[T]
```

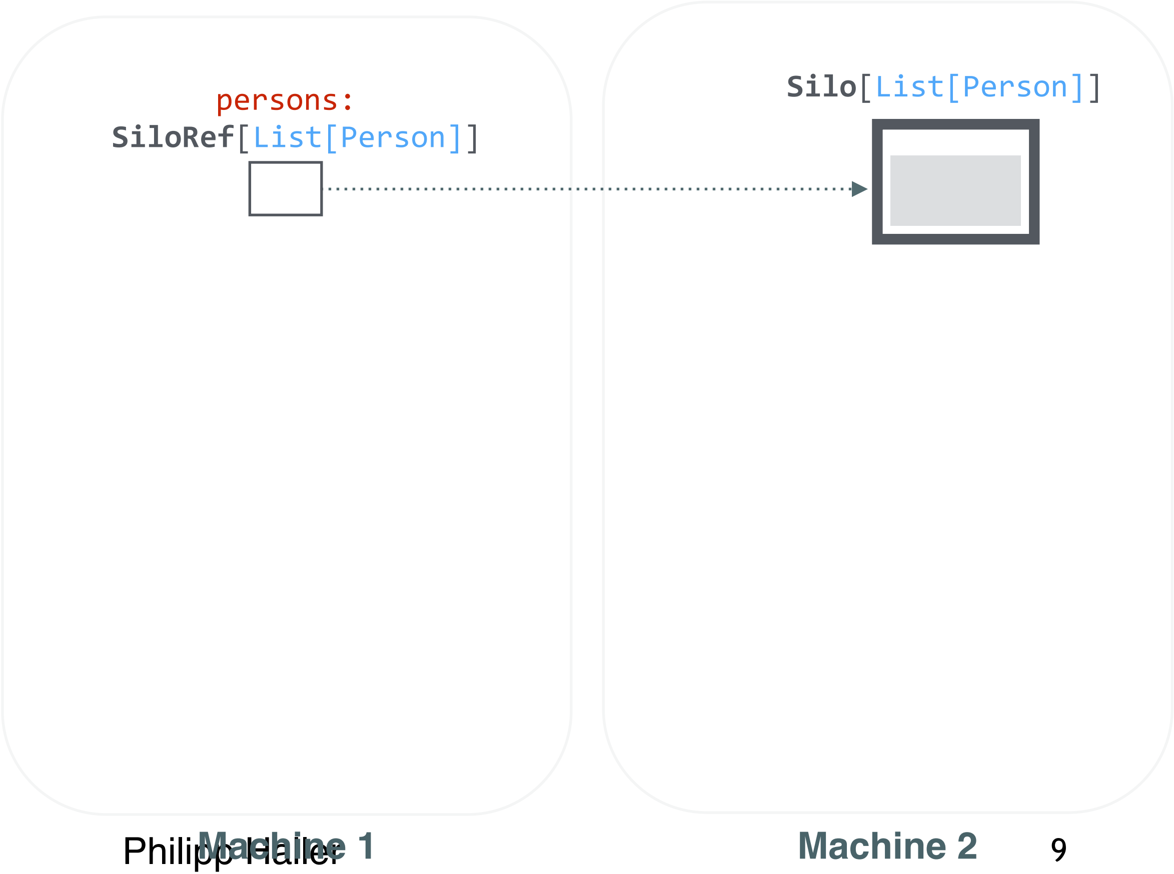
- Forces the built-up computation DAG to be sent to the associated node and applied.
- Future is completed with the result of the computation.

EAGER

More involved example

Let's make an interesting DAG!

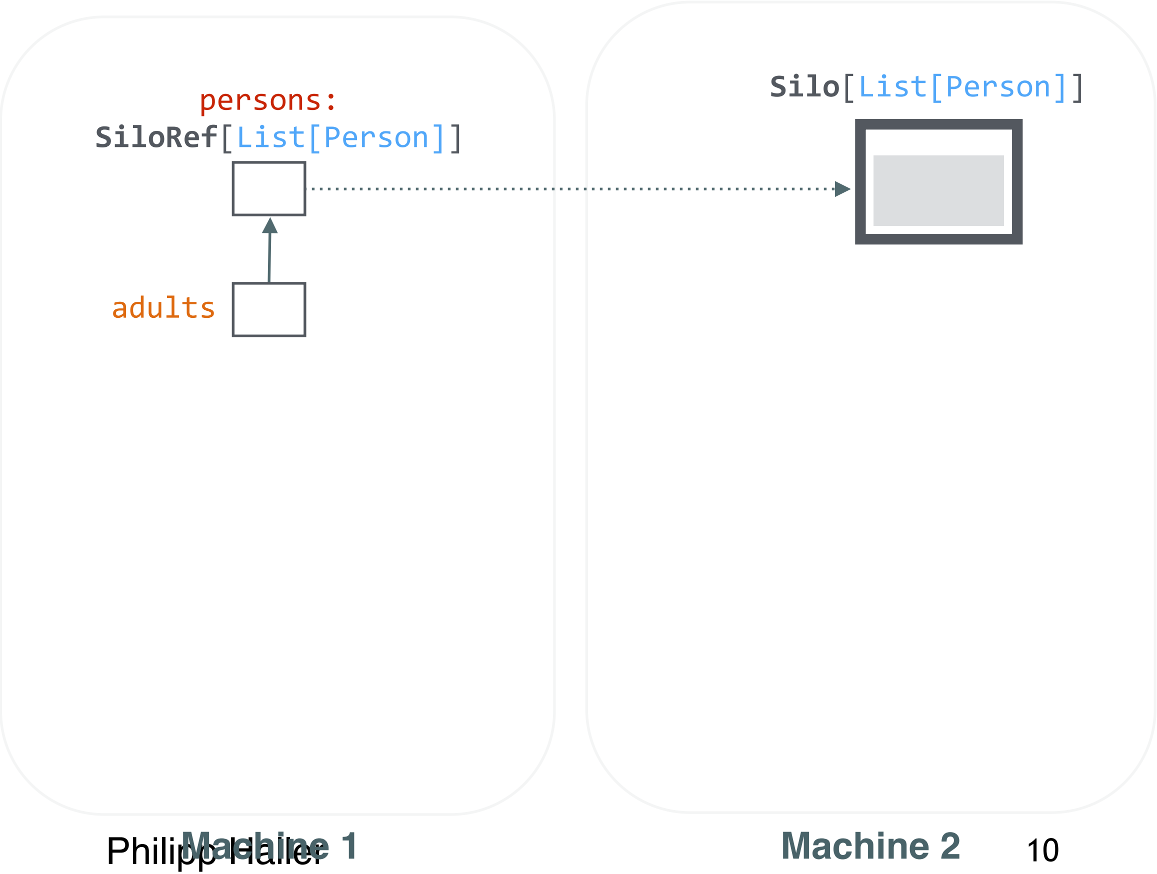
```
val persons: SiloRef[List[Person]] = ...
```



More involved example

Let's make an interesting DAG!

```
val persons: SiloRef[List[Person]] = ...
val adults =
  persons.apply(spore { ps =>
    val res = ps.filter(p => p.age >= 18)
    SiloRef.populate(currentHost, res)
  })
```



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val adults =
  persons.apply(spore { ps =>
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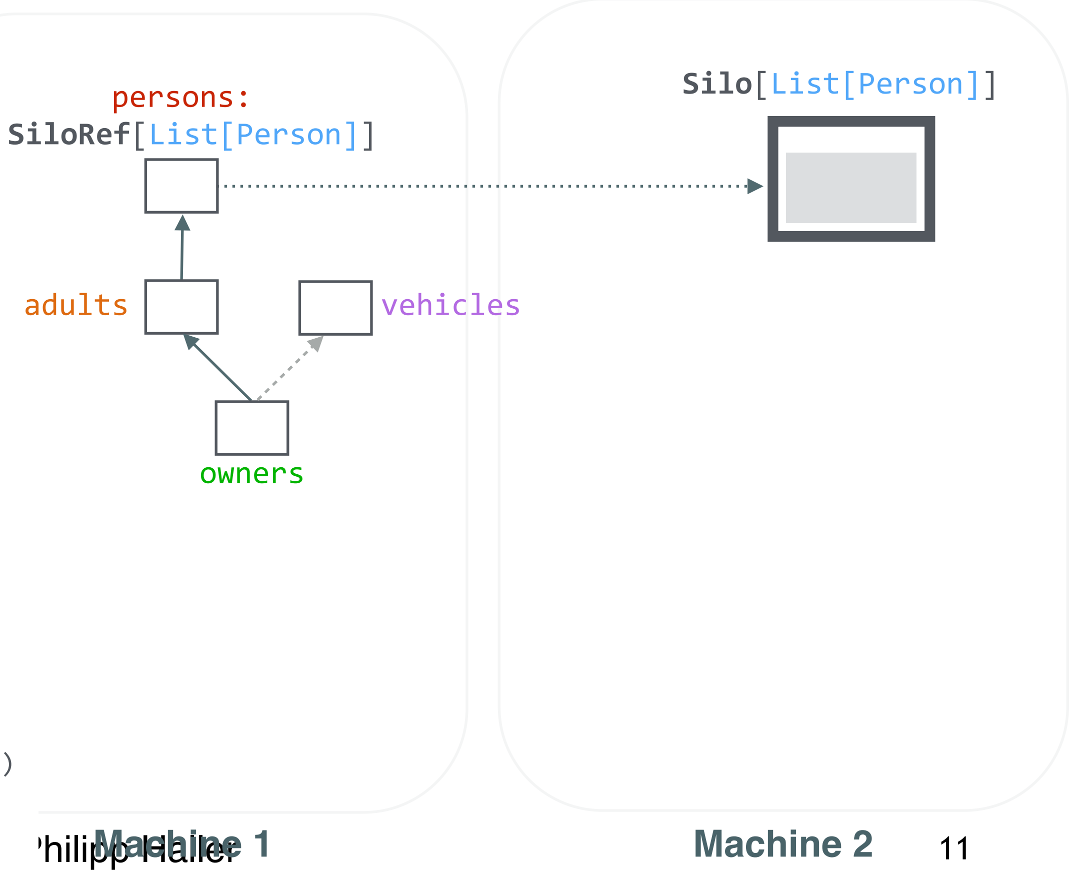
    SiloRef.populate(currentHost, res)
  })
val vehicles: SiloRef[List[Vehicle]] = ...
// adults that own a vehicle
val owners = adults.apply(spore {
  val localVehicles = vehicles // spore header
  ps =>
    localVehicles.apply(spore {
      val localps = ps // spore header
      vs =>
        SiloRef.populate(currentHost,
          localps.flatMap(p =>
            // list of (p, v) for a single person p
            vs.flatMap {
              v =>
                if (v.owner.name == p.name) List((p, v))
                else Nil
            }
          )
```



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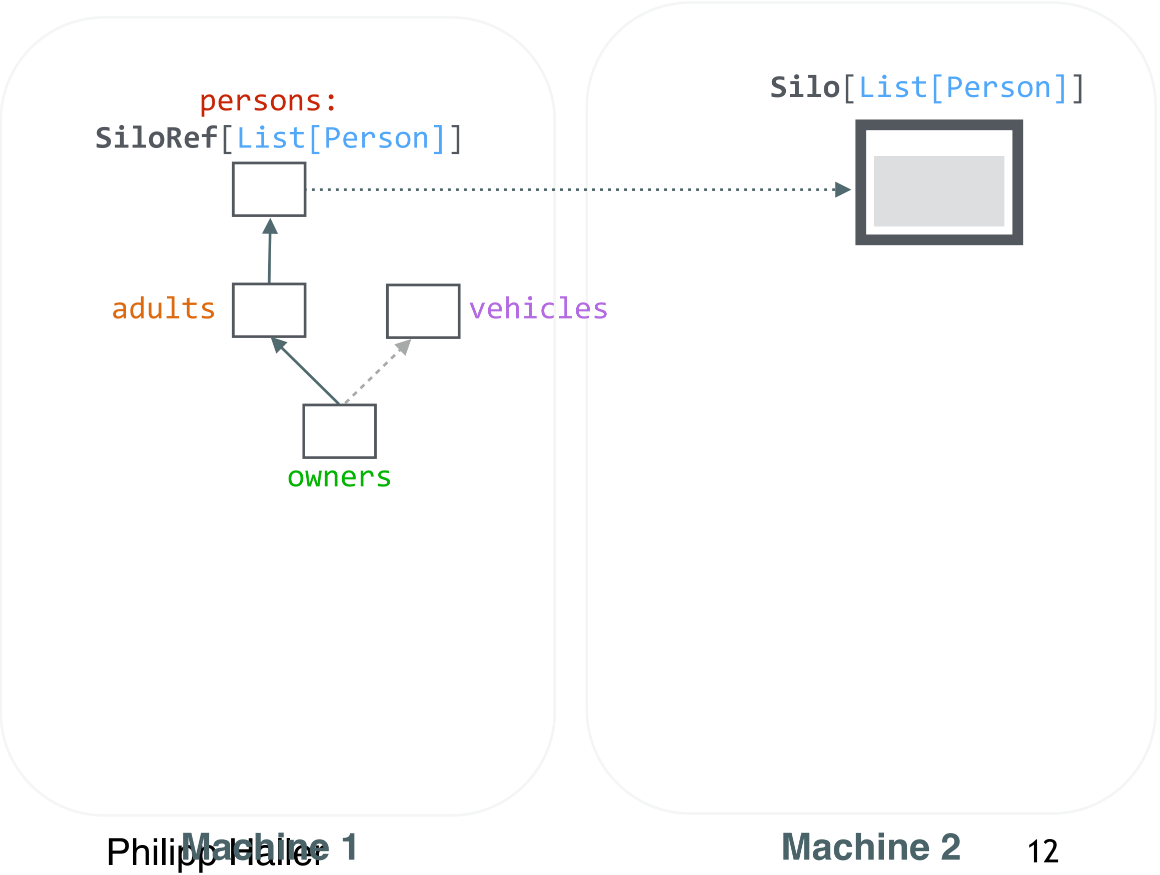
// adults that own a vehicle
val owners = adults.apply(...)
```



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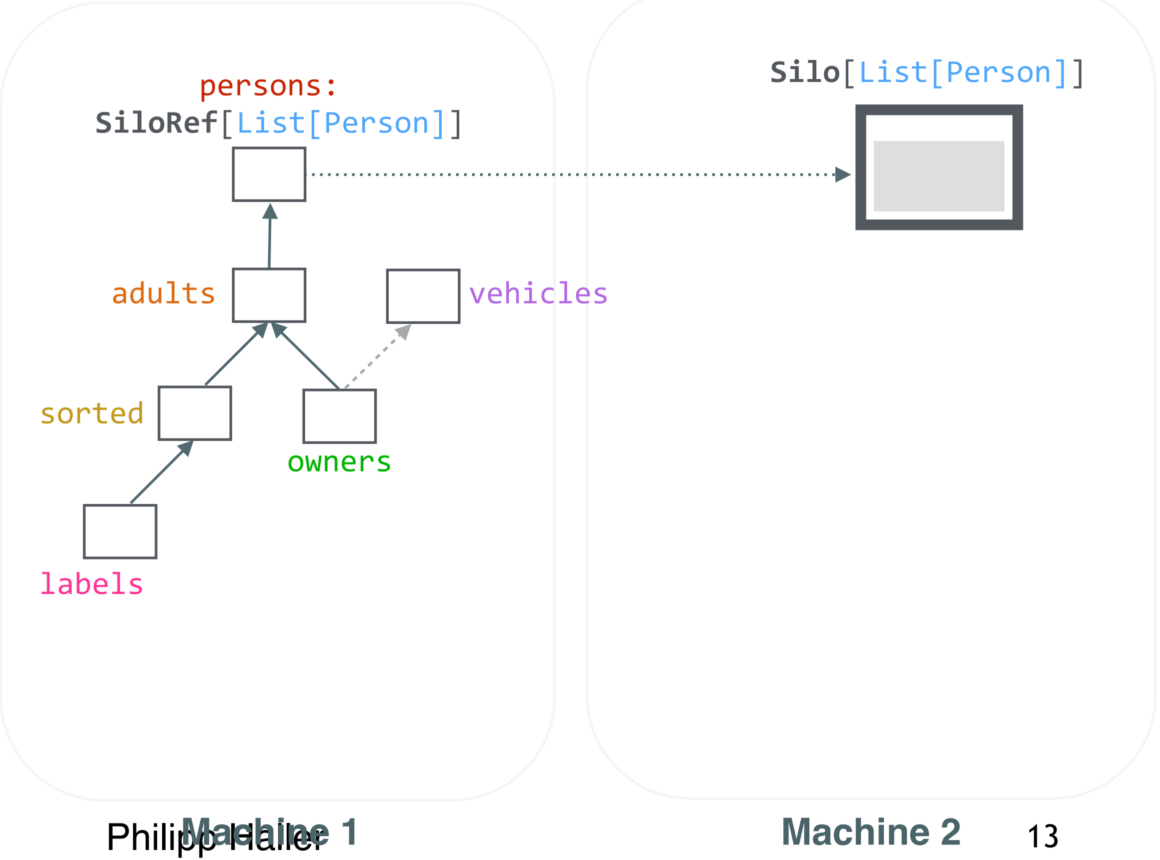
val vehicles: SiloRef[List[Vehicle]] = ...
// adults that own a vehicle
val owners = adults.apply(...)
val sorted =
  adults.apply(spore { ps =>
    SiloRef.populate(currentHost,
      ps.sortWith(p => p.age))
  })
val labels =
  sorted.apply(spore { ps =>
    SiloRef.populate(currentHost,
      ps.map(p => "Hi, " + p.name))
  })
```



More involved example

Let's make an interesting DAG!

```scala
val persons: SiloRef[List[Person]] = ...
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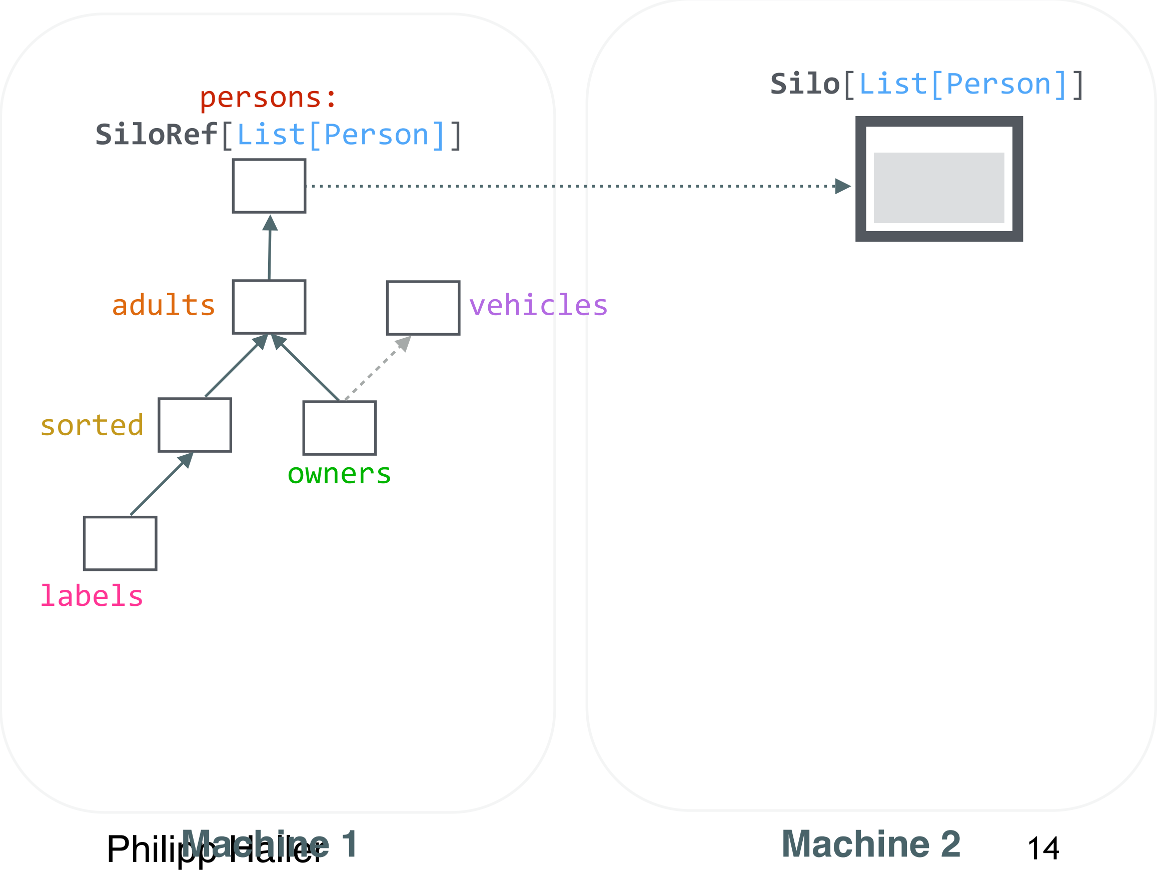
```

so far we just staged computation, we haven't yet "kicked it off".



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  })
val labels =
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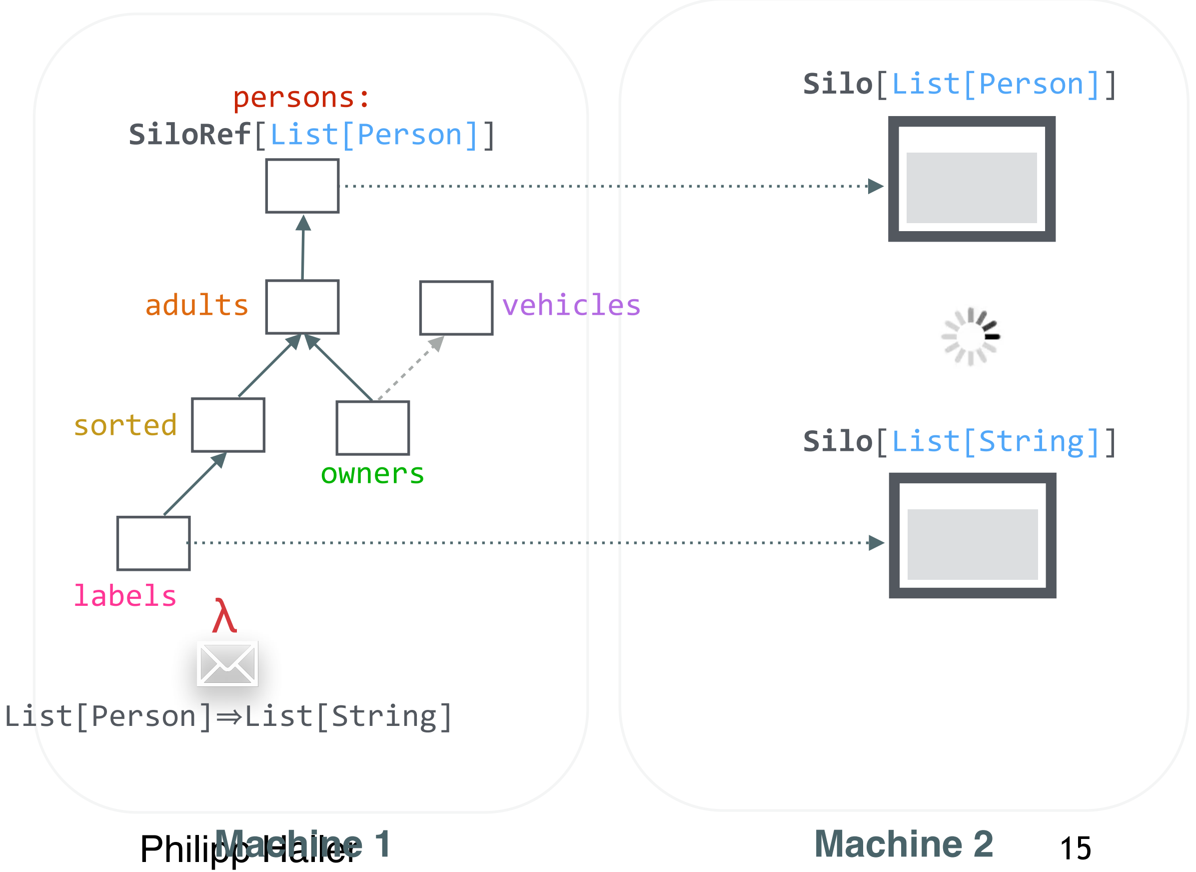
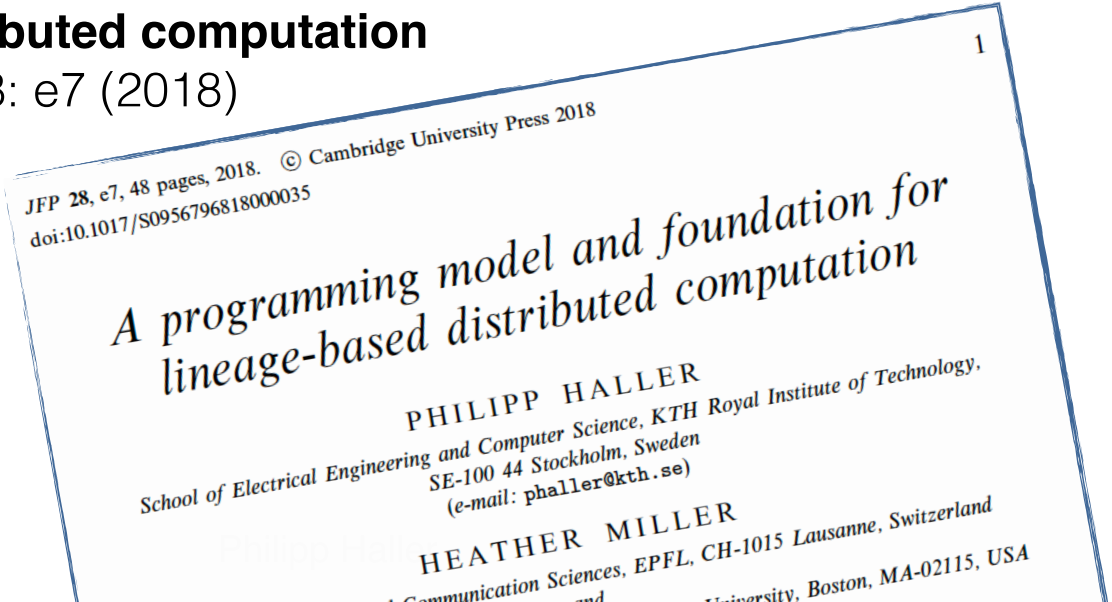
  })
labels.persist().send()
```



Lineage-based Distributed Computation: Results

- Proof establishing the ***preservation of lineage mobility***
- Proof of ***finite materialization of remote, lineage-based data***
- P. Haller, H. Miller, N. Müller: **A programming model and foundation for lineage-based distributed computation**
  J. Funct. Program. 28: e7 (2018)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JFP 28, e7, 48 pages, 2018. © Cambridge University Press 2018
doi:10.1017/S0956796818000035

A programming model and foundation for lineage-based distributed computation

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Challenge 2: Geo-Distribution

- Operating a service in multiple datacenters can ***improve latency and availability*** for geographically distributed clients
- Geo-distribution directly supported by today's cloud platforms
- *Challenge:* ***round-trip latency***
  - < 2ms between servers within the same datacenter
  - up to ***two orders of magnitude higher*** between distant datacenters

Naive reuse of single-datacenter application architectures and protocols leads to poor performance!

Data Consistency

- In order to satisfy latency, availability, and performance requirements of distributed systems, developers use ***variety of data consistency models***
  - Theoretical limit given by CAP theorem[1]
- There is no one-size-fits-all consistency model

How to *safely* use both consistent and available (but inconsistent) data within the same application?

[1] Gilbert, S., Lynch, N.: Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services. SIGACT News 33(2), 51-59 (2002)

Consistency Types: Idea

To satisfy a range of performance, scalability, and consistency requirements, provide two different kinds of replicated data types

1. ***Consistent data types***:
   - Serialize updates in a global total order: ***sequential consistency***
   - ***Do not provide availability*** (in favor of partition tolerance)
2. ***Available data types***:
   - Guarantee ***availability and performance*** (and partition tolerance)
   - ***Weaken consistency***: strong eventual consistency

Consistency Types in LCD

First-class functions

Replicated data types

LCD:

- A higher-order language with distributed references and ***consistency types***
- Values and types annotated with ***labels indicating their consistency***

$$
\begin{array}{lll}
\ell & ::= & \cdot \mid \mathsf{con} \mid \mathsf{ava} \\
t & ::= & v \mid t \bigoplus t \mid t \; \mathsf{op} \; t \mid t \; t \mid \mathtt{if} \; x \; \mathtt{then} \\
 & & \mid \mathsf{ref}_\ell \; t \mid \,!t \mid t := t \\
r & ::= & \mathsf{d} \mid \mathsf{true} \mid \mathsf{false} \mid (\lambda^\ell x : \tau. \; t) \mid \mathsf{unit} \\
v & ::= & r_\ell \mid x \\
\tau & ::= & \mathsf{Bool}_\ell \mid \mathsf{Unit}_\ell \mid \mathsf{Lat}_\ell \mid \mathsf{Ref}_\ell \; \tau \mid \tau \xrightarrow{\ell}_\ell \tau \\
\bigoplus & ::= & \vee \mid \wedge \\
\mathsf{op} & ::= & \preceq \mid \prec
\end{array}
$$

- Typed lambda-calculus
- ML-style references
- Labeled values and types

Consistency Types: Results

LCD: a higher-order language with replicated types and consistency labels

- Consistency types enable ***safe use*** of both strongly consistent and available (weakly consistent) data within the same application
- Proofs of ***type soundness*** and ***noninterference***
- Noninterference:
  Cannot observe mutations of available data via consistent data
- X. Zhao and P. Haller: **Foundations of consistency types for a higher-order distributed language**
  32nd Workshop on Languages and Compilers for Parallel Computing (LCPC 2019)
  Companion technical report with proofs:
  https://arxiv.org/abs/1907.00822

Challenge 3: Parallel Programming

- Increasing importance of ***static analysis*** (program analysis)
  - Bug finding, security analysis, taint tracking, etc.
- Precise and powerful analyses have ***long running times***
  - Infeasible to integrate into nightly builds, CI, IDE, …
  - ***Parallelization difficult:*** advanced static analyses not data-parallel
- Scaling static analyses to ever-growing software systems requires ***maximizing utilization of multi-core CPUs***

Our Approach

Ongoing work on checking correctness

- Novel ***concurrent programming model***
  - Generalization of futures/promises
  - Guarantees deterministic outcomes *(if used correctly)*
- Implemented in Scala
  - Statically-typed, integrates functional and object-oriented programming
  - Supported backends: JVM, JavaScript (+ experimental native backend)
- Integrated with OPAL, a state-of-the-art ***JVM bytecode analysis framework***

Example

- Two key concepts: ***cells*** and ***handlers***
- Cell completers permit ***writing***, cells only ***reading*** (concurrently)

```
val completer1 = CellCompleter[...]
val completer2 = CellCompleter[...]
val cell1 = completer1.cell
val cell2 = completer2.cell

cell2.when(cell1) { update =>
  if (update.value == Impure) FinalOutcome(Impure)
  else NoOutcome
}
completer1.putFinal(Impure)
```

Example

- Two key concepts: ***cells*** and ***handlers***
- Cell completers permit ***writing***, cells only ***reading*** (concurrently)

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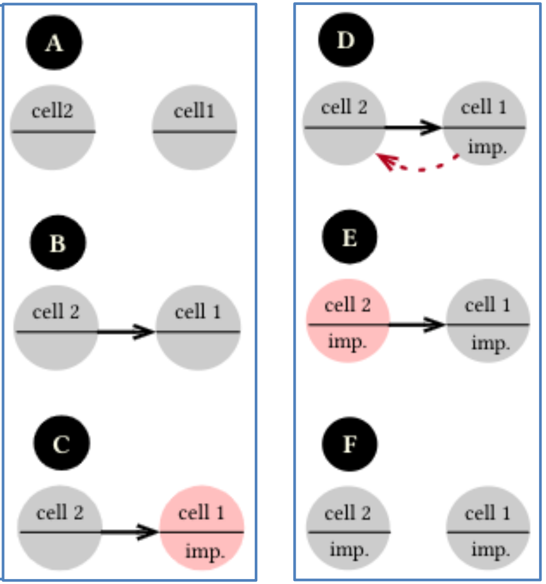
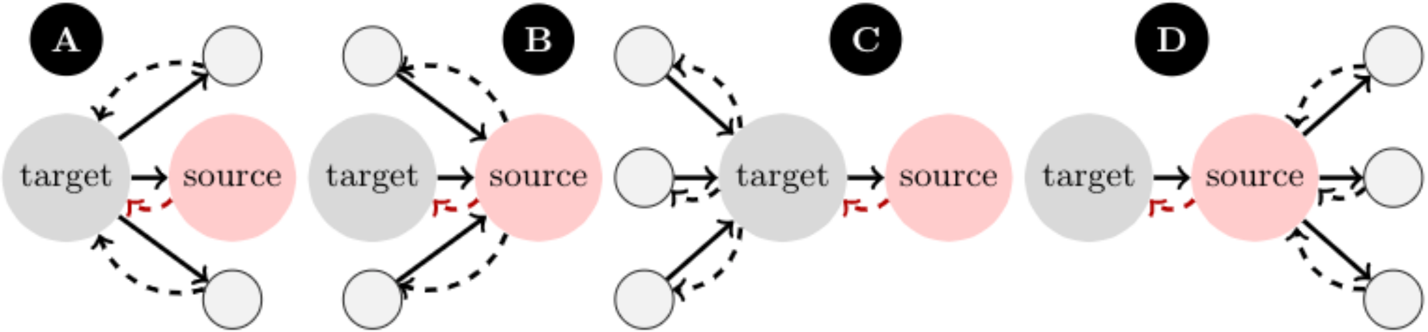
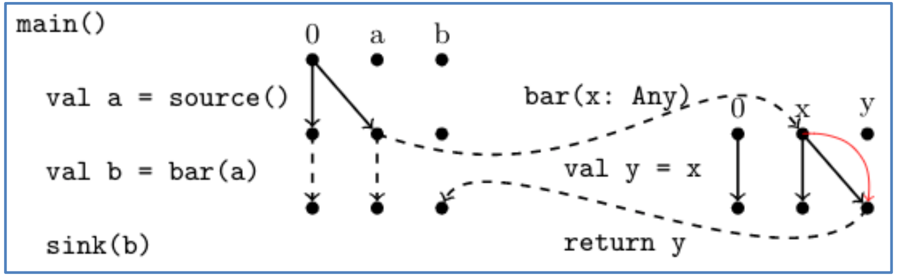


Scheduling Strategies

- ***Priorities for message propagations*** depending on number of dependencies of source/target nodes and dependees/dependers



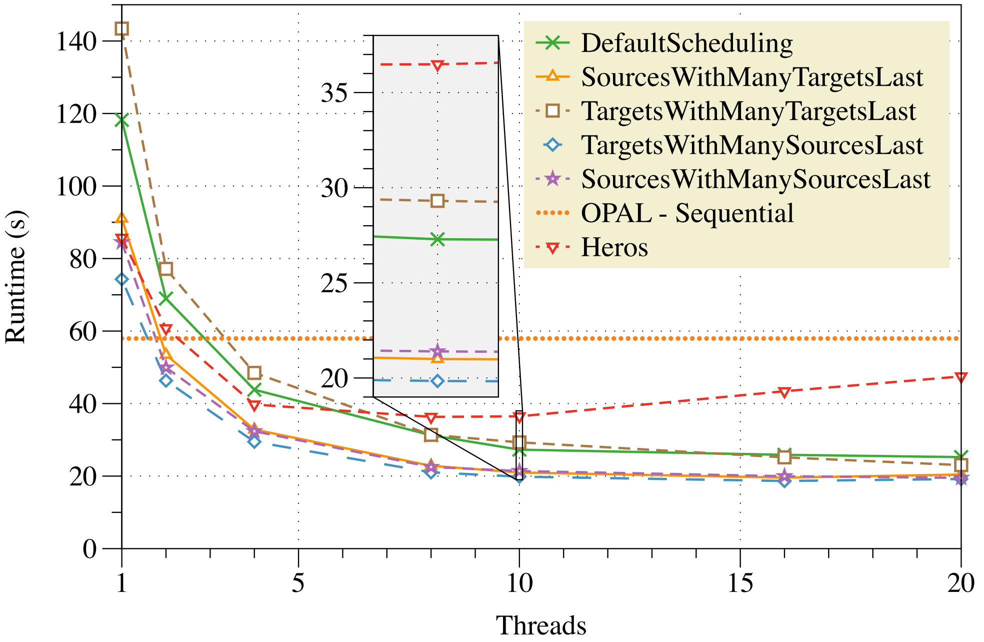
Experimental Evaluation



- Implementation of IFDS[1] analysis framework
- Use IFDS framework to implement ***taint analysis***
  - search for methods with String parameter that is later used in an invocation of `Class.forName` (i.e., reflective, dynamic class loading)

[1] Interprocedural Finite Distributive Subset

Parallel Static Analysis: Results



- Heros: best speed-up 2.36x @ 8 threads
- RANG (us): speed-up 3.53x @ 8 threads, 3.98x @ 16 threads

Analysis executed on Intel(R) Core(TM) i9-7900X CPU @ 3.30GHz (10 cores) using 16 GB RAM running Ubuntu 18.04.3 and OpenJDK 1.8_212

Conclusion

- ***Challenge:***
  Building distributed systems providing high scalability, reliability, and availability
  - System builders use various ***unsafe techniques*** to achieve these properties
  - How can we support system builders and prevent bugs?
- ***Thesis:***
  Programming language techniques can help!
  - ***Language constructs, abstractions***
    - for composing systems modularly
    - for exploiting parallelism, replication, etc.
  - ***Type systems and static analysis*** for preventing hard-to-reproduce bugs