Selected Challenges in Concurrent and Distributed Programming

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Dagstuhl Seminar 19442 on Programming Languages for Distributed Systems and Distributed Data Management

Philipp Haller: Background

- Associate professor at KTH (2014–2018 assistant professor)
  - PhD 2010 EPFL, Switzerland
- 2005–2014 ***Scala language team***
  - 2012–2014 Typesafe, Inc. (now Lightbend, Inc.)
- Co-author Scala language specification
- Focus on ***asynchronous, concurrent and distributed programming***
  - Creator of Scala actors, co-author of Scala's futures and Scala Async
  - *Topics:* programming languages, concurrent and distributed programming, type systems, semantics, static analysis

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 failures
- ***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?

Lineage-based Fault Recovery: 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)

Challenge 2: 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***

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

- 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
- Paper to appear in proceedings of LCPC 2019 (Zhao & Haller 2019)

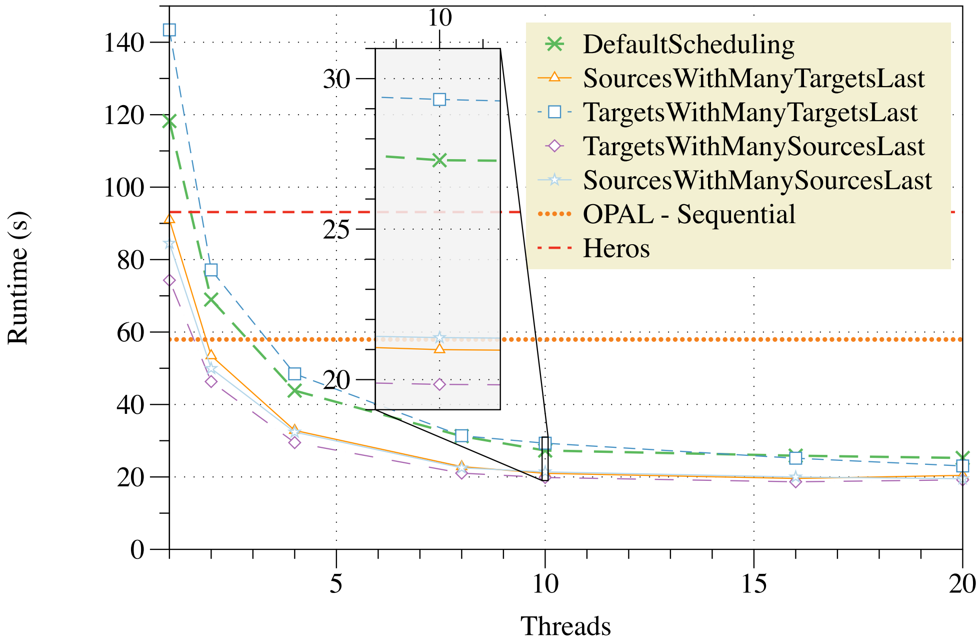
Challenge 3: Parallel Programming

- Increasing importance of static 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***

The Approach

- 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***

Parallel Static Analysis: Results



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