Causal-Consistent Debugging and Replay in Core Erlang

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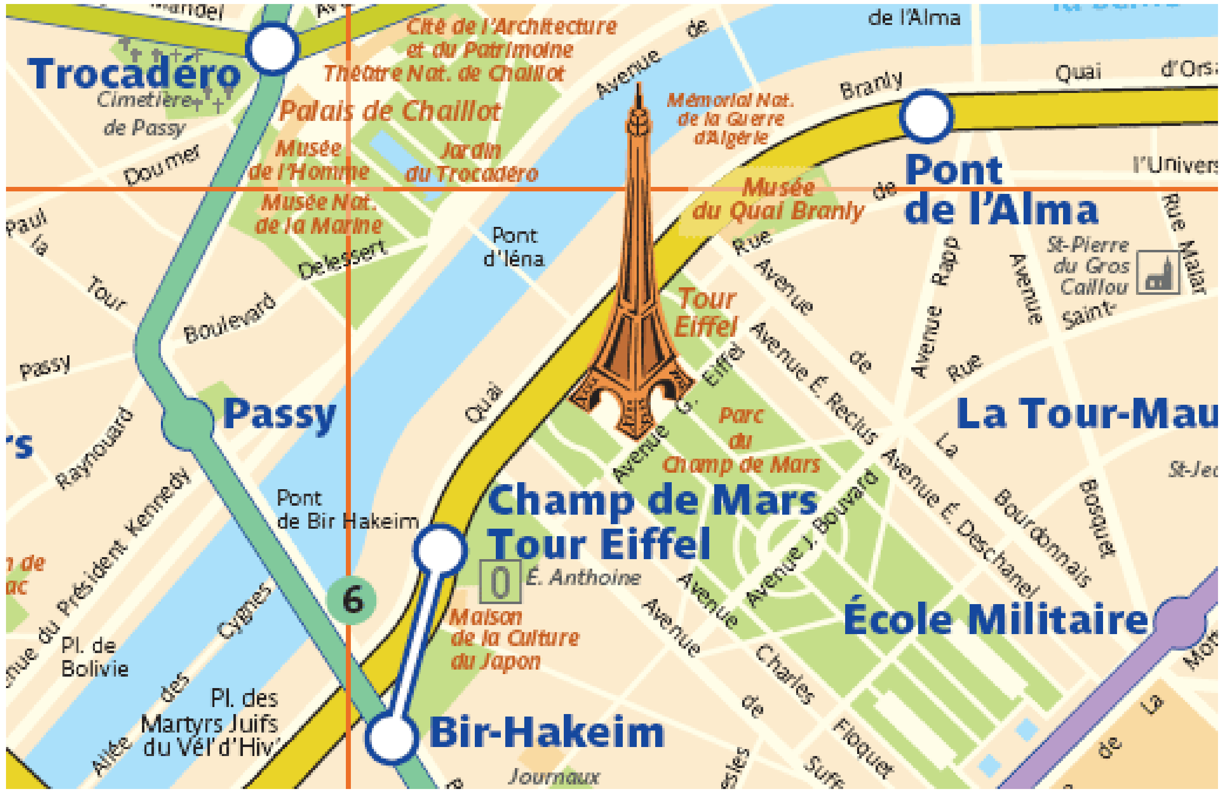
Roadmap

- Causal-consistent reversible debugging
- Causal-consistent replay
- Demo (by German)
- Formal specification
- Future directions



Reversible debugging of actor systems

- Debugging is the central topic of the DCore project
- In particular, debugging for actor systems
- Actor systems are concurrent
  - Misbehaviors may depend on the scheduling
  - Bugs may be in a different process than the one showing the misbehavior
- In Dcore, we would like to build on the work we did on CauDEr to tackle the project objectives
- CauDEr is a causal-consistent reversible and replay debugger targeting Erlang

Why Erlang can be good for this project

- German has already presented Erlang and its semantics
- Real language with a simple functional core
  - Let us look at an hello world example
  - Close to Scala + Akka
  - Much simpler than Java + Akka
- Its semantics has already been deeply studied
- CauDEr is a nice starting point
- Potential risk: the DCore proposal had more emphasis on Akka than on Erlang, ANR may complain

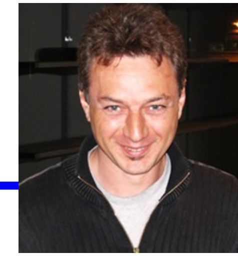
CauDEr: an overview

- A causal-consistent reversible debugger for Core Erlang
- Supports the fragment of Core Erlang presented by German
- Written in Erlang
- Includes a tracer to log a concurrent computation in the real execution environment and replay it inside the debugger
- Supported by a formal specification at the level of operational semantics

CauDEr: where to find further information

- CauDEr available at https://github.com/mistupv/cauder
- Tracer available at https://github.com/mistupv/tracer
- Described in a series of papers by (subsets of) Lanese, Nishida, Palacios & Vidal
  - LOPSTR 2016: reversible semantics of Erlang, preliminary version
  - JLAMP 2018: reversible semantics of Erlang
  - FLOPS 2018: CauDEr
  - FORTE 2019: tracer and replay

Causal-consistent reversibility



- Causal-consistent reversibility [Danos & Krivine, CONCUR 2004] is the main notion of reversibility for concurrent systems
  - Any action can be undone, provided that its consequences (if any) are undone beforehand
  - Concurrent actions can be undone in any order, but causal-dependent actions are undone in reverse order

Reversible debugging

- Extends classical debugging with the ability to explore an execution not only forward but also backward
- Supported for instance by GDB
- Operators such as “execute n steps backward”
- Avoids the classical “Oh no, I put the breakpoint too late” exclamation
  - Just execute backward from where the program stopped

Reversible debugging for concurrent systems

- In concurrent systems, one should select which process should go back (or forward)
  - Manually, or by providing a scheduler
- The selected process may not be able to go back n steps unless some other process also goes back
  - E.g., cannot undo a send unless the process that received the message undoes the receive
  - In this case the "go back n steps" command of CauDEr just stops

Reversible debugging and causality

- Causal-consistency relates backward computations with causality
- Debugging amounts to find the bug that caused a given misbehavior
- CauDEr supports the following debugging strategy: follow causality links backward from misbehavior to bug
  - Causal-consistent reversible debugging
  - Originally proposed in [Giachino, Lanese & Mezzina, FASE 2014]
  - Supported by the **roll** primitive

The **roll** primitive

- Causal-consistent debugging based on **roll** *n pid*
- Undoes the last *n* steps of process *pid*...
- ... in a causal-consistent way
  - Before undoing an action one has to undo all (and only) its consequences
  - The debugger automatically finds and undoes the consequences
- A single **roll** may cause undoing steps in many processes
- We can provide different interfaces for **roll** helping the user to select suitable *n* and *pid*
  - one for each kind of misbehavior in the language

Different interfaces for **roll**

- One interface for each possible misbehavior
- In Erlang:
  - Wrong value in a variable: **roll var** *id* goes to the state just before the variable *id* has been created
  - Unexpected message: **roll send** *msgId* goes to the state where the message *msgId* has been sent
  - Wrong message received: **roll rec** *msgId* goes to the state where *msgId* has been received
  - Unexpected process: **roll spawn** *pid* goes to the state where process *pid* has been created

Using roll-like primitives

- The programmer can follow causality links backward
- The procedure can be iterated till the bug is found
- E.g, at some point, in process p, x = 5 while we were expecting x = 10
  - **Roll var** x goes back to where x has been created
  - E.g., x taken from a message with msgId 23
  - If the message has the wrong value, use **Roll send** 23 to explore further backward
  - If a wrong message has been taken due to a wrong pattern, then the bug has been found

Properties of roll-like primitives

- Only relevant steps are undone
  - Thanks to causal consistency we undo only consequences of the target action
- No need for the programmer to know which process or expression originated the misbehavior
  - The primitives find them automatically
- Looking at which processes are involved in a **roll** execution may give useful information
  - The involvement of an unexpected process means that an interference has happened

The need for replay

- CauDEr allows the user to go back in the execution looking for the causes of a given misbehavior but…
- If the misbehavior occurs in an actual execution in production environment it is difficult to reproduce it inside the debugger
  - Common problem in debugging of concurrent systems
  - Due to nondeterminism
- If during debugging one goes too much backward, it would be good to be able to go forward again with the guarantee to replay the same misbehaviors
- Causal-consistent replay solves both these problems

Causal-consistent rollback

- It allows one to undo any action, provided that its consequences (if any) are undone beforehand
- Concurrent actions can be undone in any order, but causal-dependent actions are undone in reverse order

Causal-consistent replay

- It allows one to redo any action, provided that its causes (if any) are redone beforehand
- Concurrent actions can be redone in any order, but causal-dependent actions are redone in original order

Causal-consistent replay

- It allows one to redo any action, provided that its causes (if any) are redone beforehand
- Concurrent actions can be redone in any order, but causal-dependent actions are redone in original order
- It is the dual of causal-consistent rollback
- It allows one to redo actions which are in the future w.r.t. the current state of the computation
- The choice of the future action to redo depends on the (mis)behavior we want to replay
- How do we know the relevant future actions?

Logging

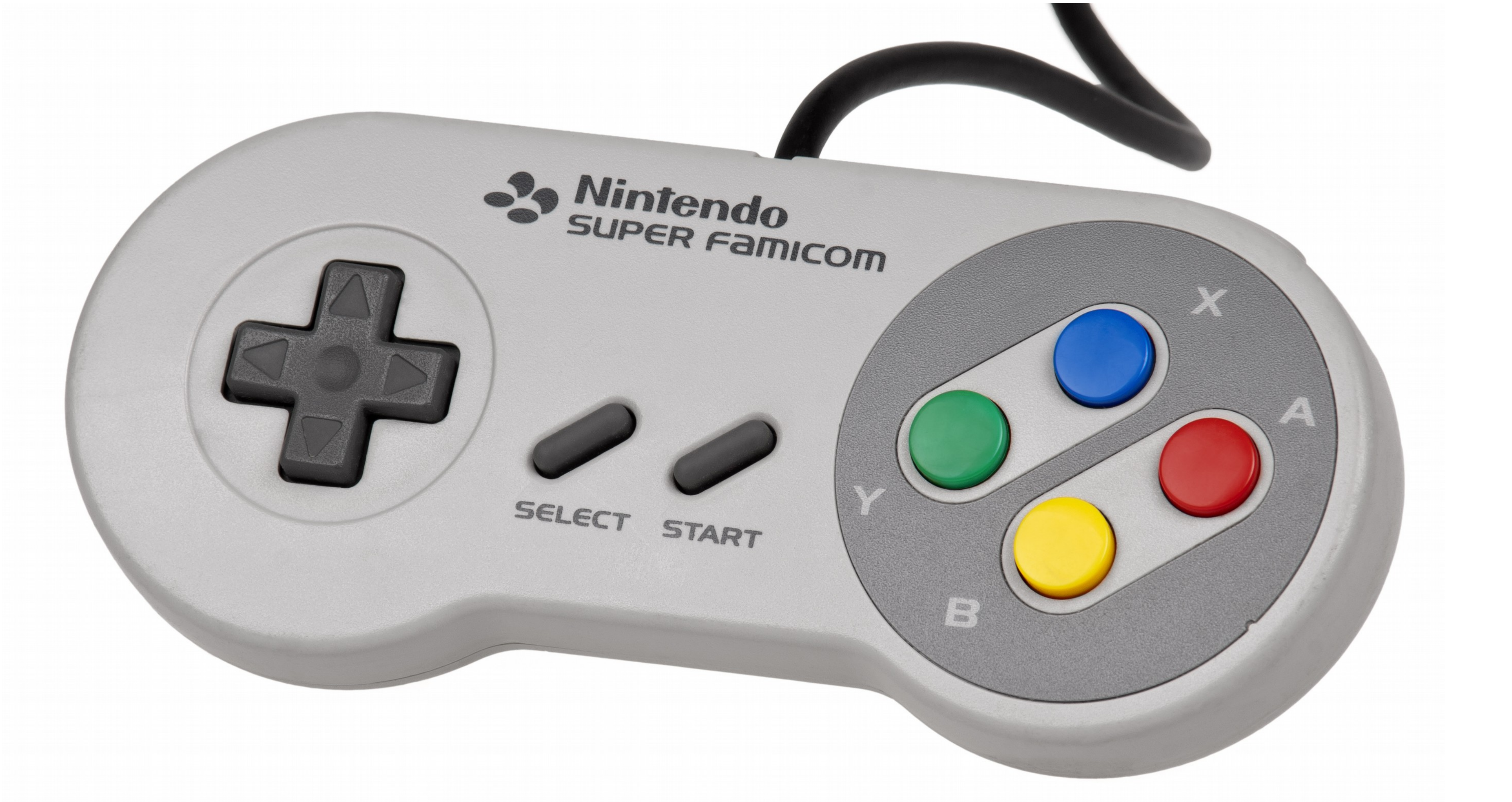
- Future actions are taken from real executions
- We built a tracer that instruments an Erlang program and produces a log for each process
- We log only concurrency-related actions
- Unique identifiers are attached to messages to match sends with receives
- The log has the form

  {73,spawn,74}   pid
  {73,send,5}
  {75,receive,7}   unique message identifier
  …
- Can also be seen as one log per process

Replay in CauDEr

- CauDEr can now take a log and allow the user to explore the logged execution
  - undo selected past actions (and their consequences)
  - redo selected future actions (and their causes)
- We always replay a computation causal equivalent to the original one
  - That is, equal up to swap of concurrent actions
  - The log should contain enough information to allow one to do this
- This is enough to replay the (mis)behaviors of the original computation

Demo, by German



Log semantics

- The log of a computation is obtained by adding labels to relevant rules of the system semantics of Erlang
- The sequence of the labels corresponds to the log

$$(\mathit{Send}) \quad \frac{\theta, e \xrightarrow{\mathsf{send}(p',v)} \theta', e' \text{ and } \ell \text{ is a fresh symbol}}{\Gamma; \langle p, \theta, e\rangle \mid \Pi \hookrightarrow_{p,\mathsf{send}(\ell)} \Gamma \cup \{(p, p', \{v, \ell\})\}; \langle p, \theta', e'\rangle \mid \Pi}$$

$$(\mathit{Receive}) \quad \frac{\theta, e \xrightarrow{\mathsf{rec}(\kappa,\overline{cl_n})} \theta', e' \text{ and } \mathsf{matchrec}(\theta, \overline{cl_n}, v) = (\theta_i, e_i)}{\Gamma \cup \{(p', p, \{v, \ell\})\}; \langle p, \theta, e\rangle \mid \Pi \hookrightarrow_{p,\mathsf{rec}(\ell)} \Gamma; \langle p, \theta'\theta_i, e'\{\kappa \mapsto e_i\}\rangle \mid \Pi}$$

$$(\mathit{Spawn}) \quad \frac{\theta, e \xrightarrow{\mathsf{spawn}(\kappa,a/n,[\overline{v_n}])} \theta', e' \text{ and } p' \text{ is a fresh pid}}{\Gamma; \langle p, \theta, e\rangle \mid \Pi \hookrightarrow_{p,\mathsf{spawn}(p')} \Gamma; \langle p, \theta', e'\{\kappa \mapsto p'\}\rangle \mid \langle p', id, \mathsf{apply}\ a/n\ (\overline{v_n})\rangle \mid \Pi}$$

Formal specification of replay and rollback

- Both replay and rollback are specified in two steps
- Uncontrolled semantics: which forward/backward steps are legal at any given point
  - It allows to replay any computation causal equivalent to the original one
  - Equal up to swap of concurrent actions and of introduction/removal of pairs do/undo or undo/redo
- Controlled semantics: which forward/backward steps are needed to replay/undo a selected future/past action

Replay uncontrolled semantics

- The syntax of processes also includes their log
- Fresh message/process identifiers are taken from logs
- Only steps compatible with the log are allowed
  - In receive we can only take the expected message

$$(\mathit{Send})\ \frac{\theta, e \xrightarrow{\mathsf{send}(p',v)} \theta', e'}{\Gamma; \langle p, \mathsf{send}(\ell)+\omega, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{send}(\ell)} \Gamma \cup \{(p, p', \{v, \ell\})\}; \langle p, \omega, \theta', e'\rangle \mid \Pi}$$

$$(\mathit{Receive})\ \frac{\theta, e \xrightarrow{\mathsf{rec}(\kappa,\overline{cl_n})} \theta', e' \quad \text{and} \quad \mathsf{matchrec}(\theta, \overline{cl_n}, v) = (\theta_i, e_i)}{\begin{array}{l}\Gamma \cup \{(p', p, \{v, \ell\})\}; \langle p, \mathsf{rec}(\ell)+\omega, \theta, e\rangle \mid \Pi \\ \qquad \rightharpoonup_{p,\mathsf{rec}(\ell)} \Gamma; \langle p, \omega, \theta'\theta_i, e'\{\kappa \mapsto e_i\}\rangle \mid \Pi\end{array}}$$

$$(\mathit{Spawn})\ \frac{\theta, e \xrightarrow{\mathsf{spawn}(\kappa,a/n,[\overline{v_n}])} \theta', e' \quad \text{and} \quad \omega' = \mathcal{L}(d, p')}{\begin{array}{l}\Gamma; \langle p, \mathsf{spawn}(p')+\omega, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{spawn}(p')} \Gamma; \langle p, \omega, \theta', e'\{\kappa \mapsto p'\}\rangle \\ \qquad \mid \langle p', \omega', id, \mathsf{apply}\ a/n\ (\overline{v_n})\rangle \mid \Pi\end{array}}$$

Rollback uncontrolled semantics

- We need history information to go back
  - Each process has its own history
- Much more detailed than the log
- E.g., at each step we store the previous expression and state, and for some actions also further information
  - Ok, this could be optimized a lot...
- All the information needed to recover the past configuration
- History is computed going forward, and consumed going backward

Computing history

(Seq)

$$\frac{\theta, e \xrightarrow{\tau} \theta', e'}{\Gamma; \langle p, \omega, h, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{seq}} \Gamma; \langle p, \omega, \mathsf{seq}(\theta, e) + h, \theta', e'\rangle \mid \Pi}$$

$(Send)$

$$\frac{\theta, e \xrightarrow{\mathsf{send}(p', v)} \theta', e'}{\Gamma; \langle p, \mathsf{send}(\ell) + \omega, h, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{send}(\ell)} \Gamma \cup \{(p, p', \{v, \ell\})\}; \langle p, \omega, \mathsf{send}(\theta, e, p', \{v, \ell\}) + h, \theta', e'\rangle \mid \Pi}$$

$(Receive)$

$$\frac{\theta, e \xrightarrow{\mathsf{rec}(\kappa, \overline{cl_n})} \theta', e' \quad \text{and} \quad \mathsf{matchrec}(\theta, \overline{cl_n}, v) = (\theta_i, e_i)}{\Gamma \cup \{(p', p, \{v, \ell\})\}\langle p, \mathsf{rec}(\ell) + \omega, h, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{rec}(\ell)} \Gamma; \langle p, \omega, \mathsf{rec}(\theta, e, p', \{v, \ell\}) + h, \theta'\theta_i, e'\{\kappa \mapsto e_i\}\rangle \mid \Pi}$$

$(Spawn)$

$$\frac{\theta, e \xrightarrow{\mathsf{spawn}(\kappa, a/n, [\overline{v_n}])} \theta', e' \quad \text{and} \quad \omega' = \mathcal{L}(d, p')}{\Gamma; \langle p, \mathsf{spawn}(p') + \omega, h, \theta, e\rangle \mid \Pi \rightharpoonup_{p,\mathsf{spawn}(p')}, \Gamma; \langle p, \omega, \mathsf{spawn}(\theta, e, p') + h, \theta', e'\{\kappa \mapsto p'\}\rangle \mid \langle p', \omega', (), id, \mathsf{apply}\ a/n\ (\overline{v_n})\rangle \mid \Pi}$$

Exploiting history

- Send and spawn can only be undone if dependencies are undone too
  - Send requires the sent message to be available in Γ
  - Spawn requires the target process to be in the initial state

$$(\overline{Seq}) \quad \Gamma; \langle p, \omega, \mathsf{seq}(\theta, e){+}h, \theta', e' \rangle \mid \Pi \leftharpoondown_{p,\mathsf{seq}} \Gamma; \langle p, \omega, h, \theta, e \rangle \mid \Pi \quad \text{where } \mathcal{V} = \mathcal{D}om(\theta') \backslash \mathcal{D}om(\theta)$$

$$(\overline{Send}) \quad \Gamma \cup \{(p, p', \{v, \ell\})\}; \langle p, \omega, \mathsf{send}(\theta, e, p', \{v, \ell\}){+}h, \theta', e' \rangle \mid \Pi \leftharpoondown_{p,\mathsf{send}(\ell)} \Gamma; \langle p, \mathsf{send}(\ell){+}\omega, h, \theta, e \rangle \mid \Pi$$

$$(\overline{Receive}) \quad \Gamma; \langle p, \omega, \mathsf{rec}(\theta, e, p', \{v, \ell\}){+}h, \theta', e' \rangle \mid \Pi \leftharpoondown_{p,\mathsf{rec}(\ell)} \Gamma \cup \{(p', p, \{v, \ell\})\}; \langle p, \mathsf{rec}(\ell){+}\omega, h, \theta, e \rangle \mid \Pi \quad \text{where } \mathcal{V} = \mathcal{D}om(\theta') \backslash \mathcal{D}om(\theta)$$

$$(\overline{Spawn}) \quad \Gamma; \langle p, \omega, \mathsf{spawn}(\theta, e, p'){+}h, \theta', e' \rangle \mid \langle p', \omega', (), id, e'' \rangle \mid \Pi \leftharpoondown_{p,\mathsf{spawn}(p')} \Gamma; \langle p, \mathsf{spawn}(p'){+}\omega, h, \theta, e \rangle \mid \Pi$$

Controlled semantics

- Rollback and replay are sequences of uncontrolled steps
- We use a recursive algorithm (modeled as a stack machine) to select the steps
- To rollback an action A in process p
  - Start undoing actions in p
  - If A is undone then stop
  - If it is not possible to undo an action due to a dependency on action A1 in p1 then rollback A1 in p1, then continue undoing A
- Replay is analogous

Properties of the uncontrolled semantics

- Uncontrolled semantics satisfies the classical properties of reversible calculi
- Loop lemma: each step can be undone
- Parabolic lemma: each computation is causal equivalent to a backward one followed by a forward one
  - Hence, no new states are introduced by reversibility
- Causal consistency theorem: two coinitial computations are cofinal iff they are causal equivalent

Properties of the controlled semantics

- Controlled rollback/replay are minimal sequences of uncontrolled steps undoing/redoing the target action
- Allows one to leverage results from the uncontrolled semantics
  - E.g., no new states are introduced by reversibility

Usefulness for debugging

- All computations in the debugger are causal equivalent to the logged one
- A local error is visible in the debugger iff it is visible in the original computation
  - Local errors are errors that involve a single process or message

Future directions

- Support Erlang instead of Core Erlang
  - Not technically difficult, but time consuming
- Support a larger subset of the language
  - Distribution, constructs for fault tolerance, ...
- Improve efficiency
  - In particular, we are currently working on reducing the time overhead due to logging
  - Particularly critical since logging needs to be done in production environment

Finally

Thanks!

Questions?