From a Mathematical Paper to Efficient Code

ASE 2017

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2017-11-01

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- GitHub: `brunjlar`

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INPUT | OUTPUT

Motivation

From a mathematical paper...

Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain

Bernardo David*, Peter Gaži**, Aggelos Kiayias***, and Alexander Russell†

October 6, 2017

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...to efficient code

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-- | Verify encrypted shares
verifyEncShares
    :: MonadRandom m
    => SecretProof
    -> Scrape.Threshold
    -> [(VssPublicKey, EncShare)]
    -> m Bool
verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
    | threshold <= 1     = error "verifyEncShares: threshold must be > 1"
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- written in Haskell

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From a mathematical paper to efficient code

- Starting point for our software is a *mathematical* paper written by *mathematicians* in *plain English*.[1]

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Question

How can we guarantee that the code we deploy faithfully translates the algorithms described in the original paper?

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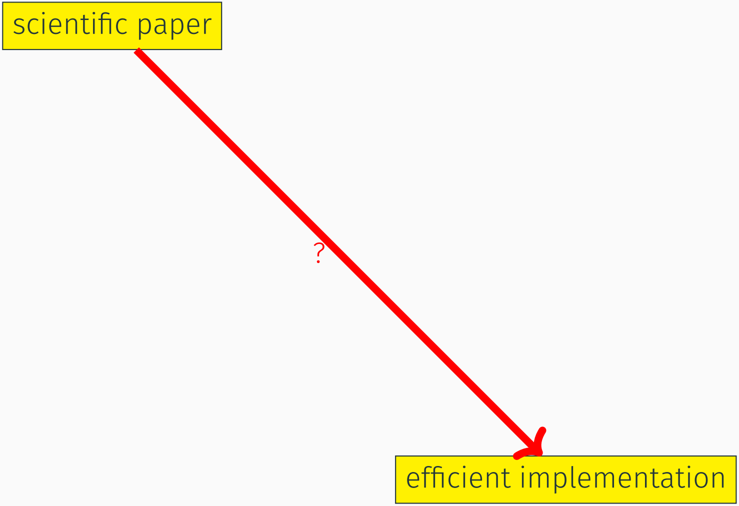
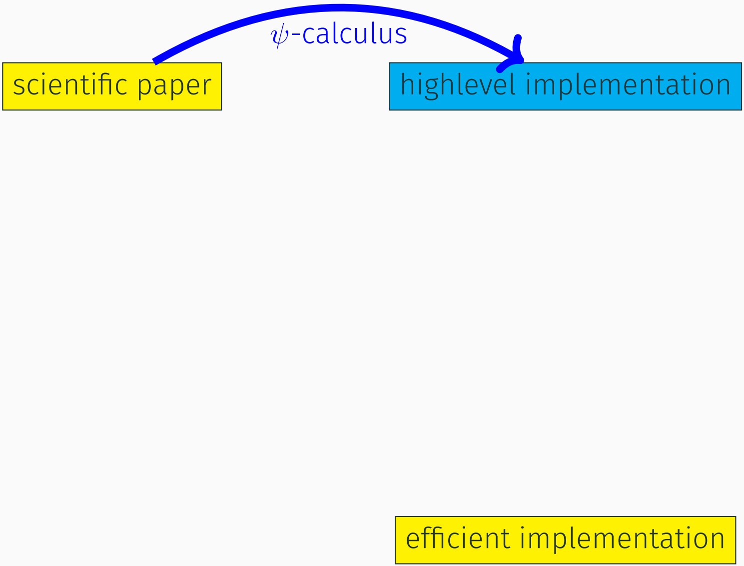
- Apart from these, we are interested in developing best practices that can be applied to a wide range of domains, pushing the envelope of what is possible and practicable.

Idea

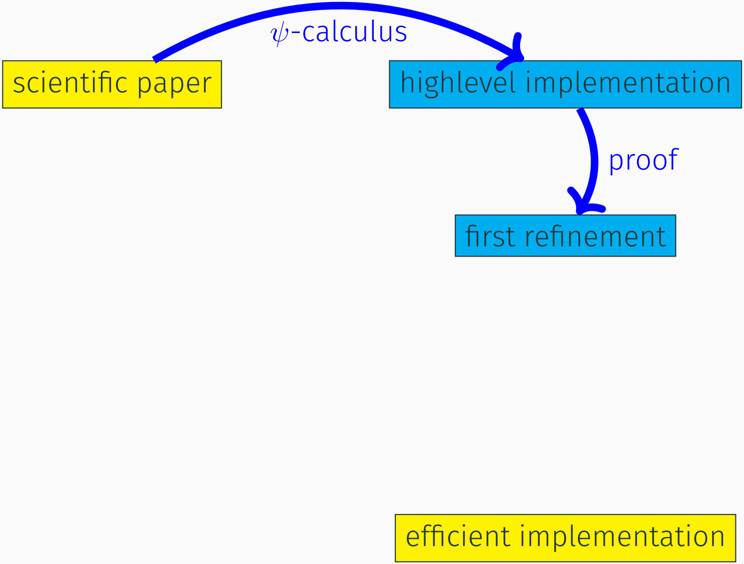


Idea

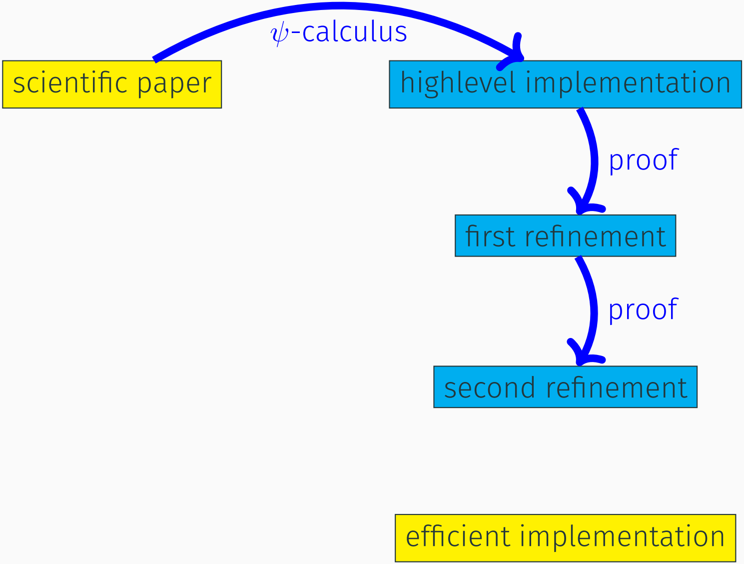


ψ-calculus
scientific paper
highlevel implementation
efficient implementation

Idea

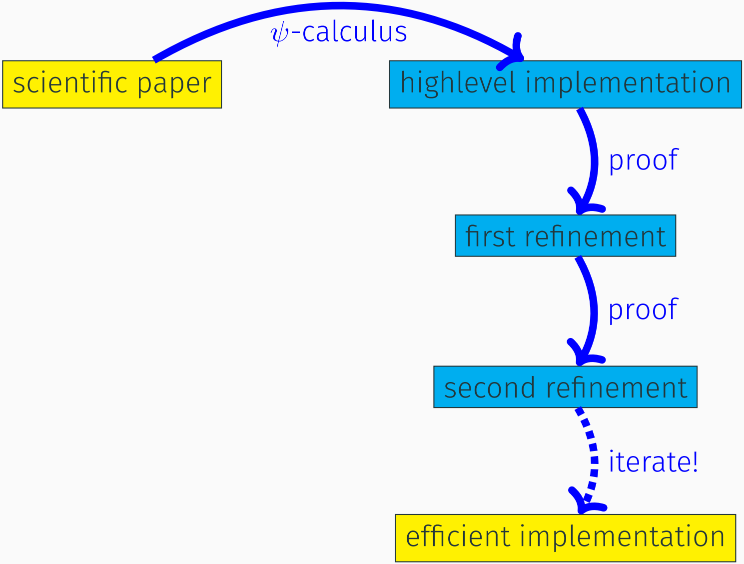

scientific paper
ψ-calculus
highlevel implementation
proof
first refinement
efficient implementation

Idea



scientific paper
ψ-calculus
highlevel implementation
proof
first refinement
proof
second refinement
efficient implementation

Idea


scientific paper
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highlevel implementation
proof
first refinement
proof
second refinement
iterate!
efficient implementation

The ψ-Calculus

From λ-calculus...

The (untyped) λ-calculus was created by Alonzo Church in the 1930s.

It is like a ”universal assembly” language for functional programming.

Very simple, only three constructs:

- variables: x,
- lambda-abstractions: $\lambda x.M$ and
- function application: MN.

The λ-calculus is Turing complete.

Example

In the λ-calculus, the identity function is $\lambda x.x$. The function $\lambda x.(\lambda y.x)$ maps an x to the constant function of value x.

...via π-calculus...

The λ-calculus is great for modelling sequential (functional) programs, put unsuitable for the description of distributed systems.

The π-calculus (Robin Milner, 1999) is for distributed systems what the λ-calculus is for sequential ones.

Where ”everything is a function” in λ-calculus, ”everything is a process” in π-calculus. There are six simple constructs in π-calculus:

- running two processes concurrently: $P \mid Q$,
- waiting for a message on a channel: $c(x).P$,
- sending a message over a channel: $\bar{c}\langle x\rangle.P$,
- replicating a process forever: $!P$,
- creating a new channel: $(\nu x)P$ and
- doing nothing: 0.

…and ψ-calculus…

In π-calculus, both channels and messages belong to the same type of names.

Even though π-calculus is very powerful (it can emulate λ-calculus and is in particular Turing-complete), many extensions have been suggested and studied (polyadic π-calculus, spi-calculus,…).

The ψ-calculus (Bengtson et al., 2011) allows (almost) arbitrary datatypes to be used as channels and messages.

In addition to the constructions from π-calculus, it offers

- conditions: φ,
- case-analysis: $\mathrm{case}\ \varphi_1 : P_1 \ [\!]\ \varphi_2 : P_2 \ [\!]\ \ldots$ and
- assertions: $(\!|\psi|\!)$.

The ψ-calculus is powerful enough to contain π-calculus and its popular extensions as special cases.

…to ψ-calculus with broadcast

There is an extension of the ψ-calculus that allows broadcasting messages (Borgström et al., 2011):

- broadcast input: $?\underline{K}N$ and
- broadcast output: $!\overline{K}N$.

This version of the ψ-calculus is flexible and powerful enough to allow a straightforward translation of (cryptographic) protocols.

There is tool support for proving properties of ψ-processes.

The calculus can also be embedded into Haskell to create programs that can actually be run.

Example protocol

A cryptographic protocol like Ouroboros Praos (David et al., 2017) can then be translated into high-level Haskell that cryptographers can understand:

```haskell
mainLoop :: SlotNumber -> SPsi BcState BcMsg ()
mainLoop sl = do
  (mmsg, _) <- bInp timeout
  case mmsg of
    Nothing                    -> mainLoop sl
    Just (BcChain c)           -> do
      isValid <- gets $ verifyAndPrune sl c
      case isValid of
        Right c' -> modify $
          \ s -> s {bcRecvChains = c' : bcRecvChains s}
        Left _   -> return ()
      mainLoop sl
    Just (BcEndSlot nextSlot) -> do
      modify bcPickMaxValid
      when (firstInEpoch nextSlot) $
        modify $ updateGenesis (epochNumber nextSlot)
      startOfSlot (slotNumber nextSlot)
```

Refinements

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So the first refinement step might be to go from chain-transmission to block-transmission.

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Using ψ-calculus tools or other formal methods, each refinement has to be proven correct.

In the end, we get an uninterrupted chain from scientific paper to efficient code.

Questions?

Thank you for your attention!

Do you have any questions?