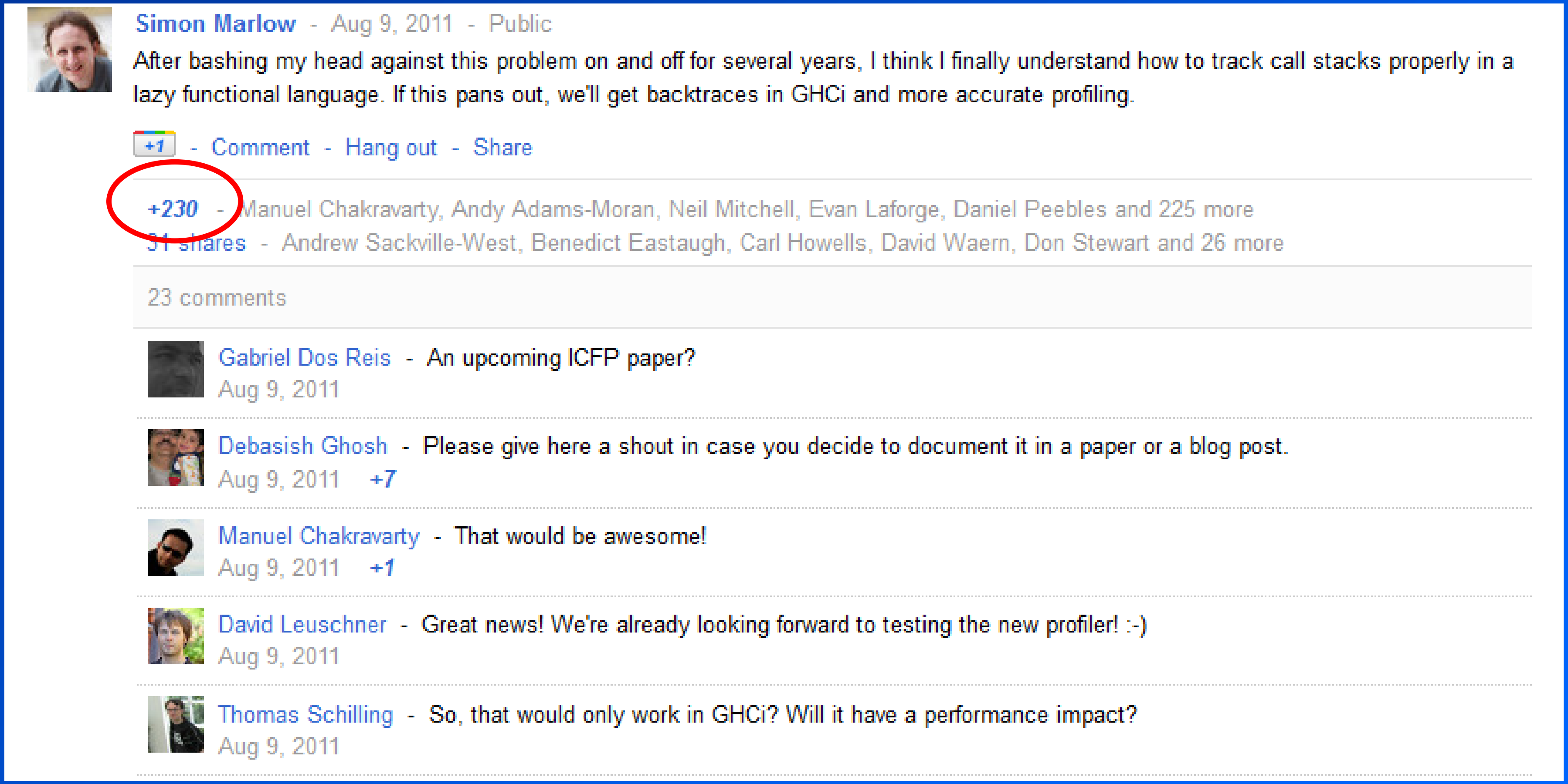
Why can’t I get a stack trace?

Simon Marlow

Motivation



Simon Marlow - Aug 9, 2011 - Public
After bashing my head against this problem on and off for several years, I think I finally understand how to track call stacks properly in a lazy functional language. If this pans out, we'll get backtraces in GHCi and more accurate profiling.
+1 - Comment - Hang out - Share
+230 - Manuel Chakravarty, Andy Adams-Moran, Neil Mitchell, Evan Laforge, Daniel Peebles and 225 more
31 shares - Andrew Sackville-West, Benedict Eastaugh, Carl Howells, David Waern, Don Stewart and 26 more
23 comments
Gabriel Dos Reis - An upcoming ICFP paper?
Aug 9, 2011
Debasish Ghosh - Please give here a shout in case you decide to document it in a paper or a blog post.
Aug 9, 2011 +7
Manuel Chakravarty - That would be awesome!
Aug 9, 2011 +1
David Leuschner - Great news! We're already looking forward to testing the new profiler! :-)
Aug 9, 2011
Thomas Schilling - So, that would only work in GHCi? Will it have a performance impact?
Aug 9, 2011

Background

- A stack trace (or lexical call context) contains a lot of information, often enough to diagnose a bug.
- In an imperative language, where every function call pushes a stack frame, the execution stack contains enough information to reconstruct the lexical call context.
- The same isn’t true in Haskell, for various reasons...

1. Tail Call Optimisation
   - TCO means that important information about the call chain is not retained on the stack
   - But TCO is essential, we can't just turn it off

```
main = do
  [x] <- getArgs
  print (f (read x))

f :: Int -> Int
f x = g (x-1)

g :: Int -> Int
g x = 100 `div` x
```

```
Execution stack:
  main
  g
```

2. Lazy evaluation

- Lazy evaluation results in an execution stack that looks nothing like the lexical call stack.
- When a computation is suspended (a *thunk*) we should capture the call stack and store it with the thunk.

```
main = do
  [x] <- fmap (fmap read) getArgs
  print (head (f x))

f x = map g [ x .. x+10 ]

g :: Int -> Int
g x = 100 `div` x
```

```
Execution stack:
  main
  print
  g
```

3. Transformation and optimisation
   - we do not want the transformations done by GHC's optimiser to lose information or mangle the call stack.
   - we've already established that strictness analysis should not distort the stack.
   - But even inlining a function will lose information if we aren't careful.

4. Even if we fix 1—3, high-level abstractions like monads result in strange stacks
   – examples coming...

- We need a framework for thinking about the issues.

A construct for pushing on the stack

```
push L E
```

- "push label L on the stack while evaluating E"
- this is a construct of the source language *and* the intermediate language (Core)
- Compiler can add these automatically, or the user can add them
- Think {-# SCC .. #-} in GHC
- We get to choose how detailed we want to be:
  - exported functions only
  - top-level functions only
  - all functions (good for profiling)
  - call sites (good for debugging)
  - all sub-expressions (fine-grained debugging or profiling)

- Define stacks:

```
type Stack = [Label]
push :: Label -> Stack -> Stack
call :: Stack -> Stack -> Stack
```

- Define stacks:

```
type Stack = [Label]
push :: Label -> Stack -> Stack
call :: Stack -> Stack -> Stack
```

stack at the call site

- Define stacks:

```
type Stack = [Label]
push :: Label -> Stack -> Stack
call :: Stack -> Stack -> Stack
```

stack at the call site

stack of the function

- Define stacks:

```
type Stack = [Label]
push :: Label -> Stack -> Stack
call :: Stack -> Stack -> Stack
```

stack at the call site

stack of the function

stack for the call

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

Executable semantics

current stack

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk,
eval stk (ELam x e)   = return (stk, ELam

eval stk (EPush l e) = eval (push l stk)

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

E is a State monad containing the Heap: a mapping from Var to (Stack,Expr)

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

Values are straightforward

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

push L on the stack, evaluate the body

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval
   eval lam_stk (subst y x e)
```

suspend the computation e1 on the heap, capture the current stack

Executable semantics

```
eval :: Stack -> Expr -> E (Stack,Expr)

eval stk (EInt i)     = return (stk, EInt i)
eval stk (ELam x e)   = return (stk, ELam x e)

eval stk (EPush l e) = eval (push l stk) e

eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EApp f x) = do
   (lam_stk, ELam y e) <- eval stk f
   eval lam_stk (subst y x e)
```

Application continues with the stack returned by evaluating the lambda

Executable semantics (variables)

```
eval stk (EVar x)  = do
   r <- lookupHeap x
   case r of
     (stk', EInt i)   -> return (stk', EInt i)
     (stk', ELam y e) -> return (call stk stk’, ELam y e)

     (stk',e) -> do
        deleteHeap x
        (stkv, v) <- eval stk' e
        insertHeap x (stkv,v)
        eval stk (EVar x)
```

Here’s where we are “calling” a function

Given this semantics, define push & call

- The problem now is to find suitable definitions of push and call that
  - Behave like a call stack
  - Have nice properties:
    - transformation-friendly
    - predictable/robust
    - implementable

Lazy evaluation is dealt with

- Lazy evaluation is dealt with by
  - capturing the current stack when we suspend a computation as a thunk in the heap
  - temporarily restoring the stack when the thunk is evaluated
- Nothing controversial at all – we just need a mechanism for capturing and restoring the stack.

```
eval stk (ELet (x,e1) e2) = do
   insertHeap x (stk,e1)
   eval stk e2

eval stk (EVar x)  = do
   r <- lookupHeap x
   case r of
     ...

     (stk',e) -> do
        deleteHeap x
        (stkv, v) <- eval stk' e
        insertHeap x (stkv,v)
        eval stk (EVar x)
```

Tail calls are dealt with

- The semantics says nothing about tail calls – push always pushes on the stack.
- Even if the underlying execution model is doing TCO, the call stack simulation must not.

Examples

```
f = λx. push “f” x+x

main = λx. push “main”
           let y = 1 in f y
```

- The heap is initialised with the top-level bindings (give each the stack <CAF>)
- When we get to (f y), current stack is <main>
- f is already evaluated
- call <main> <CAF> = <main>
- eval <main> (push f y+y)
- eval <main,f> (y+y)
- at the +, the current stack is <main,f>

Let’s assume, for now, call Sapp Slam = Sapp

Use the call-site stack?

```
call sapp slam = sapp
```

- Previous example suggests this might be a good choice?
- After all, *this gives exactly the call stack you would get in a strict language*

But we have to be careful

- If instead of this:

```
f = λx. push "f" x+x

main = λx. push "main"
            let y = 1 in f y
```

- We wrote this:

```
f = push "f" (λx . x+x)

main = λx. push "main"
            let y = 1 in f y
```

- Now it doesn't work so well: the "f" label is lost.
- In this semantics, *the scope of push does not extend into lambdas*

Just label all the lambdas?

- Idea: make the compiler label all the lambdas automatically
- e.g. the compiler inserts a push inside any lambda:

```
f = push "f" (λx . push "f1" x+x)

main = λx. push "main"
           let y = 1 in f y
```

- Now we get a useful stack again: <main,f1>

Some properties

- Adding an extra binding doesn't change the stack

```
f = push "f" (λx . push "f1" x+x)

g = push "g" f

main = λx. push "main"
           let y = 1 in g y
```

- In this semantics 'push L x == x'
- arguably useful: the stack is robust with respect to this transformation (by the compiler or user)

But…

- eta-expansion changes the stack

```
f = push "f" (λx . push "f1" x+x)

g = λx . push "g" f x

main = λx. push "main"
           let y = 1 in g y
```

- Now the stack at the + will be <main,g,f>

Concrete example

- When we tried this for real, we found that in functions like

```
h = f . g
```

- h does not appear on the stack, although in

```
h x = (f . g) x
```

- now it does. This is surprising and undesirable.

Worse…

- Let’s make a state monad:

```
newtype M s a = M { unM :: s -> (s,a) }

instance Monad (M s) where
  (M m) >>= k = M $ λs -> case m s of
                               (s',a) -> unM (k a) s'
  return a = M $ λs -> (s,a)

errorM :: String -> M s a
errorM s = M $ λ_ -> error s

runM :: M s a -> s -> a
runM (M m) s = case m s of (_,a) -> a
```

Suppose we want the stack when error is called, for debugging

Using a monad

- Simple example:

```
main = print (runM (bar ["a","b"]) "state")

bar :: [String] -> M s [String]
bar xs = mapM foo xs

foo :: String -> M s String
foo x = errorM x
```

Using a monad

- Simple example:

```
main = print (runM (bar ["a","b"]) "state")

bar :: [String] -> M s [String]
bar xs = mapM foo xs

foo :: String -> M s String
foo x = errorM x
```

- We are looking for a stack like <main,runM,bar,mapM,foo,errorM>

Using a monad

- Simple example:

```
main = print (runM (bar ["a","b"]) "state")

bar :: [String] -> M s [String]
bar xs = mapM foo xs

foo :: String -> M s String
foo x = errorM x
```

- We are looking for a stack like <main,runM,bar,mapM,foo,errorM>
- Stack we get: <runM>

Why?

- Take a typical monadic function:

```
f = do p; q
```

- Desuraging gives

```
f = p >> q
```

- Adding push:

```
f = push “f” (p >> q)
```

- Expanding out (>>):

```
f = push “f” (λs -> case p s of (a,s’) -> b s’)
```

- recall that push L (λ x . e) = λ x. e

The IO monad

- In GHC the IO monad is defined like the state monad given earlier.
- We found that with this stack semantics, we get no useful stacks for IO monad code at all.
- When profiling, all the costs were attributed to main.

call S_{app} S_{lam} = S_{app}?

- We recovered the non-lazy non-TCO call stack, which is the stack you would get in a strict functional language.

- But it isn't good enough.
  – at least when used with monads or other high-level functional abstractions

Can we find a better semantics?

- call S_{app} S_{lam} = ?
- non-starter: call S_{app} S_{lam} = S_{lam}
  - ignores the calling context
  - gives a purely lexical stack, not a call stack
  - (possibly useful for flat profiling though)
- Clearly we want to take into account both S_{app} and S_{lam} somehow.

The definitions I *want* to use

```
call Sapp Slam = Sapp ++ Slam’
  where (Spre, Sapp’, Slam’) = commonPrefix Sapp Slam

push l s | l `elem` s  =  dropWhile (/= l) s
         | otherwise   =  l : s
```

- Behaves nicely with inlining:
  - “common prefix” is intended to capture the call stack up to the point where the function was defined
- useful for profiling/debugging: the top-of-stack label is always correct, we just truncate the stack on recursion.

Status

- GHC 7.4.1 has a new implementation of profiling using push
- +RTS –xc prints the call stack when an exception is raised
- Programmatic access to the call stack:

Status

- GHC 7.4.1 has a new implementation of profiling using push
- +RTS –xc prints the call stack when an exception is raised
- Programmatic access to the call stack:

```
-- | like 'trace', but additionally prints a call
-- stack if one is available.
traceStack :: String -> a -> a

-- | like ‘error’, but includes a call stack
errorWithStackTrace :: String -> a
```

Demo

Programmatic access to stack trace

- The GHC.Stack module provides runtime access to the stack trace
- On top of which is built this:

- e.g. now when GHC panics it emits a stack trace (if it was compiled with profiling)

Programmatic access to stack trace

- The GHC.Stack module provides runtime access to the stack trace
- On top of which is built this:

```
-- | like 'trace', but additionally prints a call stack if one is
-- available.
traceStack :: String -> a -> a
```

- e.g. now when GHC panics it emits a stack trace (if it was compiled with profiling)

Properties

- This semantics has some nice properties.

```
push L x             => x

push L (λx . e)      => λx . e
push L (C x1 .. xn) => C x1 .. xn


let x = λy . e in push L e'
    => push L (let x = λy . e in e')

push L (let x = e in e')
   => let x = push L e in push L e
```

Properties

- This semantics has some nice properti

```
push L x            => x

push L (λx . e)     => λx . e
push L (C x1 .. xn) => C x1 .. xn


let x = λy . e in push L e'
    => push L (let x = λy . e in e')

push L (let x = e in e')
   => let x = push L e in push L e
```

since the stack attached to a lambda is irrelevant (except for heap profiling)

Properties

- This semantics has some nice properties.

```
push L x              => x

push L (λx . e)       => λx . e
push L (C x1 .. xn) => C x1 .. xn


let x = λy . e in push L e'
    => push L (let x = λy . e in e')

push L (let x = e in e')
   => let x = push L e in push L e
```

O(1) change to cost attribution, no change to profile shape

Properties

- This semantics has some nice properties.

```
push L x            => x

push L (λx . e)     => λx . e
push L (C x1 .. xn) => C x1 .. xn


let x = λy . e in push L e'
    => push L (let x = λy . e in e')

push L (let x = e in e')
   => let x = push L e in push L e
```

Note if e is a value, the push L will disappear

Inlining

- We expect to be able to substitute a function's definition for its name without affecting the stack. e.g.

```
f = λx . push "f1" x+x

main = λx. push "main"
           let y = 1 in f y
```

- should be the same as

```
main = λx. push "main"
           let y = 1 in
           (λx . push "f1" x+x) y
```

- and indeed it is in this semantics.
  - (inlining functions is crucial for optimisation in GHC)

Think about what properties we want

- Push inside lambda:

```
push L (λx. e)   ==   λx. push L e
```

  - (recall that the previous semantics allowed dropping the push here)
  - This will give us a push that scopes over the inside of lambdas, not just outside.
    - which will in turn give us that stacks are robust to eta-expansion/contraction

What does it take to make this true?

- Consider

```
let f = push "f" λx . e
in  ... f ...
```

```
let f = λx . push "f" e
in  ... f ...
```

- If we work through the details, we find that we need

```
call S (push L Sf)  ==  push L (call S Sf)
```

- Not difficult: e.g.

```
type Stack = [Label]
push = (:)
call = foldr push
```

like flip (++), but useful to define it this way

Recursion?

- We do want finite stacks
  - the mutator is using tail recursion
- Simplest approach: push is a no-op if the label is already on the stack somewhere:

```
push l s  | l `elem` s  =  s
          | otherwise   =  l : s
```

- still satisfies the push-inside-lambda property
- but: not so good for profiling or debugging
  - the label on top of the stack is not necessarily where the program counter is

Inlining of functions

- (remember, allowing inlining is crucial)
- Consider

```
let g = λx.e in
let f = push "f" g in
f y
```

```
let f = push "f" λx.e in
f y
```

- Work through the details, and we need that

```
call (push L S) S  ==  push L S
```

- interesting: calling a function whose stack is a prefix of the current stack should not change the stack.

Break out the proof tools

Break out the proof tools

- QuickCheck.

Break out the proof tools

- QuickCheck.

```
prop_append2 = forAllShrink stacks shrinkstack $ \s ->
               forAll Main.labels $ \x ->
                      call (s `push` x) s == s `push` x

*** Failed! Falsifiable (after 8 tests and 2 shrinks):
(E :> "e") :> "b"
"e"
```

Break out the proof tools

- QuickCheck.

```
prop_append2 = forAllShrink stacks shrinkstack $ \s ->
               forAll Main.labels $ \x ->
                     call (s `push` x) s == s `push` x

*** Failed! Falsifiable (after 8 tests and 2 shrinks):
(E :> "e") :> "b"
"e"
```

- but this corresponds to something very strange:

Break out the proof tools

- QuickCheck.

```
prop_append2 = forAllShrink stacks shrinkstack $ \s ->
               forAll Main.labels $ \x ->
                      call (s `push` x) s == s `push` x

*** Failed! Falsifiable (after 8 tests and 2 shrinks):
(E :> "e") :> "b"
"e"
```

- but this corresponds to something very strange:

```
push “f”
...
let g = λx.e in
let f = push “f” g in
f y
```

A more restricted property

- This is a limited form of the real property we need for inlining
- The push-inside-lambda property behaves similarly: we need to restrict the use of duplicate labels to make it go through.

A more restricted property

```
prop_stack2a = forAllShrink stacks shrinkstack $ \s ->
                forAll Main.labels $ \x ->
                     x `elemstack` s ||
                     call (s `push` x) s == s `push` x

*Main> quickCheck prop_stack2a
+++ OK, passed 100 tests.
```

- This is a limited form of the real property we need for inlining
- The push-inside-lambda property behaves similarly: we need to restrict the use of duplicate labels to make it go through.