

GHC's RISC-V Native Code Generation Backend

- Haskell Implementors' Workshop 2025
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RISC-V Overview

RISC-V

- 32bit **R**educed **I**nstruction **S**et as base
 - RV32I *Base Integer Instruction Set* → ~40 instructions, ~6 formats
 - Basic interpreter can be built in an afternoon
- Augmented by many extensions (sub-standards)
 - ISA like playing with Lego bricks
- Custom extensions are anticipated by the ISA
- Ideal research vehicle for computer architectures

RISC-V

- **ISA is open source**, implementations (SOCs) not necessarily
 - License: *Creative Commons Attribution 4.0 International*
 - Development on GitHub
 - Vibrant community
 - Conceptualization in working groups at *RISC-V International* foundation
 - Free membership for individuals
- Everyone is free to build a RISC-V processor:
 - Several vendors
 - Hobbyists

RISC-V Status

- Standard (ISA, Calling Convention, ...) pretty complete
- Lack of powerful hardware
 - No good cloud options → No native cloud CI
 - Cores comparable to ARM A55 (2017)
 - Your smartphone might be more powerful than RISC-V SBCs

RISC-V Status

- Lot's of movement though
 - New boards and chips appear frequently
 - Many manufacturers
 - Research all over the world
 - EU grant for RISC-V HPC research
 - DARE (Digital Autonomy with RISC-V in Europe)
 - Funding: ~240 Million Euros
 - SHAKTI CPU by IIT-Madras (India)
 - many more

RISC-V Status

- There are still some dragons ...
 - Tools don't support the full instruction set
 - Tools sometimes still have bugs ...
 - Cores may have bugs
 - Core may not adhere to the ratified standards because it pre-dates it

Warning

Use latest releases and be very precise about the hardware and build target!

ISA naming scheme

- Start with a base ISA: RV32I, RV64I or RV64E
- Add the extensions in canonical order
 - RV64IM (*Extension for Integer Multiplication and Division*)
- Extensions can imply others
 - F (*Extension for Single-Precision Floating-Point*) implies Zicsr (*Extension for Control and Status Register (CSR) Instructions*)
- Extension can be versioned
 - Format: <extension><major>p<minor> (parts can be optional)
 - The ISA is pretty new, so extensions' versions can usually be ignored
- Reduce common extensions to sets (e.g. *General for IMAFDZicsr_Zifencei*)

Profiles

- *Profiles* (e.g. RVA23) define minimum requirements to simplify this
 - Otherwise, buying and building for a consumer computer could be a nightmare
 - (It still is, because many vendors don't mention profiles yet on their marketing pages)
 - Linux distributions handle this by relying on a small extension set (usually *RV64GC*)
 - *G*: General
 - *C*: Compressed instructions

GHC Implementation Status

GHC RISC-V History

- LLVM backend by Andreas Schwab (October 2020; GHC 9.2)
- Moritz Angerman and Sven Tennie accidentally started NCG at the same time
 - Moritz switched to mentor role
 - Sven continued to hack
 - Andreas built CI support at SuSE with patch files
 - <https://build.opensuse.org/package/show/openSUSE:Factory/ghc>
- Available from **GHC 9.12**



Tip

Reach out and team up

- I wouldn't have imagined that such great collaboration between former strangers would be possible.

GHC RISC-V status

- LLVM Backend
- RTS Linker
- Native Code Generation Backend
 - Fullfills whole testsuite (minus SIMD tests)
- Tier 3 platform
 - Due to lack of powerful hardware (CI), there are no official binary distributions, yet
 - Probably not much in use, yet
 - Happy to receive bug reports!
- SIMD (Vector) in NCG support WIP

Vector (SIMD) Support

Vector Register Configuration

- Problem: Applications need very different vector sizes
 - Embedded chips should save silicon
 - HPC may need big vectors
 - usually a tradeoff
 - usually max vector sizes are bound to ISA features
 - Standard allows 32 (*Zv32b*) to 65,536 bits per vector register

Vector Register Configuration

- RISC-V approach:
 1. Make effective register width configurable → **grouping**
 - Combine multiple vector registers to one effective
 2. Tell when a configuration doesn't fit → **strip mining**
 - Iterate over vector chunks
- Benefits:
 - Application can dynamically react on the vector register width (VLEN)
 - HPC software can run on embedded CPUs and vice versa without recompilation

Vector Register Configuration Instruction(s)

```
vsetivli <VL>, <AVL>, <SEW>, <LMUL>, <tail>, <mask>
```

- **VL** : New, effective **V**ector **L**ength (in elements)
- **AVL** : **A**pplication **V**ector **L**ength
 - The desired VL
- **SEW** : **S**ingle **E**lement **W**idth
 - Width of an element: **e8** , **e16** , **e32** , **e64** (bits)
- **LMUL** : **L**ength **M**ultiplier
 - **mf8** (LMUL=1/8), **mf4** (LMUL=1/4), **mf2** (LMUL=1/2)
 - **m1** (LMUL=1), **m2** (LMUL=2), **m4** (LMUL=4), **m8** (LMUL=8)

Vector configuration - Grouping

- Increment each element of a *8bit x 8* vector by one (128bit register width)

```
void plus_one(uint8_t b[8]) {  
    for(int i = 0; i < 8; i++) {  
        b[i]++;  
    }  
}
```

- `mf2` grouping: $1/2 * 128 = 64$
- required bits: $8 * 8 = 64$

```
plus_one:  
    vsetivli zero, 8, e8, mf2, ta, ma  
    # Load v8 as 8-bit elements at address in a0  
    vle8.v v8, (a0)  
    # v8[i] = v8[i] + 1  
    vadd.vi v8, v8, 1  
    # Store to address in a0  
    vse8.v v8, (a0)  
    ret
```

Vector configuration - Grouping (2)

- Increment each element of a *8bit x 16* vector by one (128bit register width)

```
void plus_one(uint8_t b[16]) {  
    for(int i = 0; i < 16; i++) {  
        b[i]++;  
    }  
}
```

- `m1` grouping: $1 * 128 = 128$
- required bits: $8 * 16 = 128$

```
plus_one:  
    vsetivli zero, 16, e8, m1, ta, ma  
    # Load v8 as 8-bit elements at address in a0  
    vle8.v v8, (a0)  
    # v8[i] = v8[i] + 1  
    vadd.vi v8, v8, 1  
    # Store to address in a0  
    vse8.v v8, (a0)  
    ret
```

Vector configuration - Grouping (3)

- Increment each element of a *8bit* x 32 vector by one (128bit register width)

```
void plus_one(uint8_t b[32]) {  
    for(int i = 0; i < 32; i++) {  
        b[i]++;  
    }  
}
```

- m2 grouping: $2 * 128 = 256$
- required bits: $8 * 32 = 256$

```
plus_one:  
    # 32 doesn't fit into an immediate, use a register  
    li a1, 32  
    vsetvli zero, a1, e8, m2, ta, ma  
    # Load v8 as 8-bit elements at address in a0  
    vle8.v v8, (a0)  
    # v8[i] = v8[i] + 1  
    vadd.vi v8, v8, 1  
    # Store to address in a0  
    vse8.v v8, (a0)  
    ret
```

Vector configuration - Strip-Mining

- Increment each element of a $8\text{bit} \times 32$ vector by one (128bit register width)

```
void plus_one(uint8_t b[32]) {  
    for(int i = 0; i < 32; i++) {  
        b[i]++;  
    }  
}
```

- Iterations (after `vsetvli`):

- `t0 = 16; a1 = 32; a0 = &b[0] = b`
- `t0 = 16; a1 = 16; a0 = &b[16] = b + 16`

```
plus_one:  
    # Start with 32 elements  
    li a1, 32  
  
loop:  
    # Configure to get the real VL (16) in t0  
    vsetvli t0, a1, e8, m1, ta, ma  
    # Perform computation on chunk  
    vle8.v v8, (a0)  
    vadd.vi v8, v8, 1  
    vse8.v v8, (a0)  
    # Update pointers and counters for next chunk  
    # Move pointer forward: a0 += VL  
    add a0, a0, t0  
    # Reduce remaining elements (a1 -= VL)  
    sub a1, a1, t0  
    # Repeat if there are remaining elements  
    bnez a1, loop  
  
end:  
    ret
```

Vector configuration - Strip-Mining

- Increment each element of a *8bit* \times **17** vector by one (128bit register width)

```
void plus_one(uint8_t b[17]) {  
    for(int i = 0; i < 17; i++) {  
        b[i]++;  
    }  
}
```

- Iterations (after `vsetvli`):

- `t0` = 16; `a1` = 17; `a0` = `&b[0]` = `b`
- `t0` = 1; `a1` = 1; `a0` = `&b[16]` = `b + 16`

```
plus_one:  
    # Start with 17 elements  
    li a1, 17  
  
loop:  
    # Configure to get the real VL in t0  
    vsetvli t0, a1, e8, m1, ta, ma  
    # Perform computation on chunk  
    vle8.v v8, (a0)  
    vadd.vi v8, v8, 1  
    vse8.v v8, (a0)  
    # Update pointers and counters for next chunk  
    # Move pointer forward: a0 += VL  
    add a0, a0, t0  
    # Reduce remaining elements (a1 -= VL)  
    sub a1, a1, t0  
    # Repeat if there are remaining elements  
    bnez a1, loop  
  
end:  
    ret
```

Vectors: Questions to investigate

- How can we allocate register groups? (Virtual registers that cover multiple consecutive registers)
 - This would require the register allocator to be aware of grouped registers
- Would it be better to apply strip-mining?
 - Would that work for all `MachOp`s?

Note

The first edition of SIMD / vectors support in NGC will:

- have a GHC parameter for a minimum VLEN (vector register width)
- expect the machine to have at least that VLEN
- panic when a bigger vector is requested

Vectors: Questions to investigate

- How to optimize for minimal vector re-configuration?
 - My naive approach is to:
 - fold over the final instructions in the Assembly emitting stage (`Ppr.hs`)
 - drop duplicated configuration statements in a block
 - This ignores optimizations by moving instructions with the same configuration.

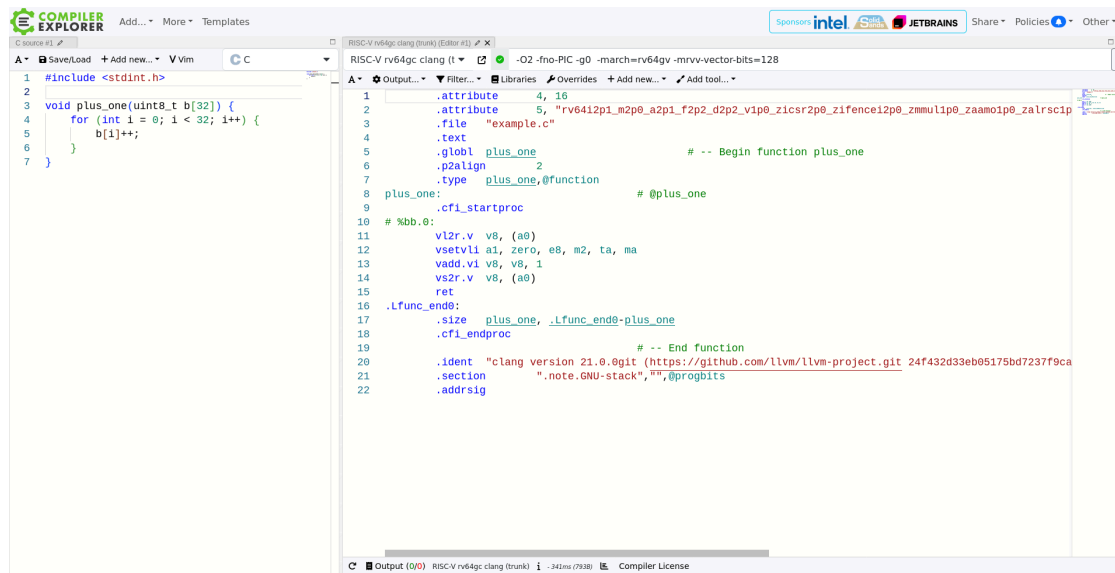
General future tasks

- Investigate ISA standard extensions beyond RV64GV
 - Good candidates may be:
 - **B**: Extension for Bit Manipulation
 - **Zicond**: Extension for Integer Conditional Operations
- Let GHC understand the target machine string
 - The *naming scheme* we discussed in the beginning
- Check if applying GADTs couldn't make NCGs saver
 - The current pattern is often "(pattern) match or panic"

NCG development: Tipps & Tricks

Compiler Explorer (Godbolt)

- <https://godbolt.org>
- Learn from others
- C and LLVM IR are good choices
- Intrinsics are a typed way to play with Assembly



The screenshot displays the Compiler Explorer (Godbolt) interface. The left pane shows the source code in C, and the right pane shows the generated assembly code for the RISC-V rv64gc target.

Source Code (C):

```
1 #include <stdint.h>
2
3 void plus_one(uint8_t b[32]) {
4     for (int i = 0; i < 32; i++) {
5         b[i]++;
6     }
7 }
```

Assembly Code (RISC-V rv64gc):

```
1      .attribute      4, 16
2      .attribute      5, "rv64i2p1_m2p0_a2p1_f2p2_d2p2_v1p0_zicsr2p0_zifence12p0_zmmul1p0_zaamo1p0_zalrsc1p
3      .file            "example.c"
4      .text
5      .globl plus_one      # -- Begin function plus_one
6      .p2align          2
7      .type             plus_one,@function
8
9 plus_one:
10     .cfi_startproc
11     # %bb.0:
12     vl2r.v v8, (a0)
13     vsetvli a1, zero, e8, m2, ta, ma
14     vadd.vi v8, v8, 1
15     vs2r.v v8, (a0)
16     ret
17
18 .lfunc_end0:
19     .size plus_one, .lfunc_end0-plus_one
20     .cfi_endproc
21
22     # -- End function
23     .ident "clang version 21.0.0git (https://github.com/llvm/llvm-project.git 24f432d33eb85175bd7237f9ca
24     .section          ".note.GNU-stack","",@progbits
25     .addrsig
```

ghc.nix

- <https://gitlab.haskell.org/ghc/ghc.nix>
- Nix env to build GHC
 - Cross-compiler envs possible

```
cd $MY_GHC_SRC_DIR
nix develop "git+https://gitlab.haskell.org/ghc/ghc.nix#riscv64-linux-cross"
./boot && configure_ghc
```

- More convenient with `direnv` `.envrc` file
 - `direnv` automatically provides the environment when you change into the directory

```
use flake git+https://gitlab.haskell.org/ghc/ghc.nix\#riscv64-linux-cross
```

Run tests emulated with Qemu

- Most tests can be executed with an emulator (e.g. Qemu)
 - You don't have access to real hardware
 - Your workstation is faster
 - ...

```
CROSS_EMULATOR=qemu-riscv64 hadrian/build -j --docs=none --flavour=devel2 test
```

test-primops

- <https://gitlab.haskell.org/ghc/test-primops>
- QuickCheck tests for PrimOps
- Compares your GHC to another version
 - Cross possible



Tip

test-primops doesn't test all MachOps (CmmExprs). Adding (some of) them would be a great newcomers' task.

Build GHC and libs with LLVM

- Focus on small bits: One at a time
- Build GHC itself and libraries with `-fllvm`
- Build tests with `-fasm`
 - `EXTRA_HC_OPTS=-fasm hadrian/build test ...`
- `hadrian` provides:
 - a flavour transformer `<your-flavour>+llvm`
 - a flavour that uses LLVM `quick-cross`

Reduce problems

- Adjust tests
 - Focus on one test / feature at a time
 - Build the smallest reproducer possible
 - Reading a lot of Assembly or Cmm can be very exhausting
 - Add dump options: `-ddump-to-file -dppr-debug -ddump-cmm -ddump-asm`
 - Run `hadrian` with `-k` to keep those files
 - Write small Cmm reproducers by hand
 - E.g. write a small Haskell driver and call it via FFI
- Run testsuite subsets with `hadrian`

Your are not alone!

- Matrix group (with IRC bridge): <https://matrix.to/#/#GHC:matrix.org>
- Mailing list: <https://mail.haskell.org/cgi-bin/mailman/listinfo/ghc-devs>
- Discourse: <https://discourse.haskell.org>

Hunting Heisenbugs

- Bugs that disappear when you "look" at them
 - Trace logs and debuggers (GDB) change the timing of programs and execution at CPU-level
- Trace instructions and/or CPU state with Qemu
 - `qemu-riscv64 -d in_asm,cpu -one-insn-per-tb`
- My worst Heisenbug was a missing memory barrier (program cache flush, `fence.i` instruction) in the linker
 - Illegal instruction exceptions at weird places
 - Gone when the timing changed e.g. by adding trace logs
 - Staring at Qemu traces gives hints what happened shortly before
 - Though, it slows the execution down immensely!

AI / LLMs

- Large Language Models are pretty good in explaining Assembly code

