GNU Jitter and the illusion of simplicity or Copying, patching and combining compiler-generated code in executable memory The Anarchist's guide to GCC or The fun of playing with fire

> Luca Saiu http://ageinghacker.net positron@gnu.org

> > GNU Project

Binary T00ls Summit 2022

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http://ageinghacker.net GNU Jitter and GCC: the fun of playing with fire



BTS 2022

Hello future viewers

The following resources are for those watching a recording of this presentation who want to occasionally pause the video and follow along:

• Source tarball for Structured, including GNU Jitter as a sub-package http://ageinghacker.net/bts2022/structured-simple-1.0. tar.gz (recommended)

- Source tarball for GNU Jitter, including Structured as a sub-package (yes, this is not a mistake), requiring bootstrap with the Autotools to compile Structured as in this demo: http://ageinghacker.net/bts2022/jitter-0.9.285.tar.gz
- Git source repository http://git.ageinghacker.net/jitter, requiring bootstrap with the Autotoools plus Flex, GNU Bison, GNU Texinfo and so on. Use the tag binary-tools-summit-2022 to get today's version.



- Late 2016: I wanted to make GNU epsilon faster. Disappointed by threaded-code VMs;
- 2017: Read many scientific papers about making threaded-code VMs faster, mostly from Anton Ertl and the other GForth people (I recommend [Ertl and Gregg, 2004]); added my own ideas, generalised. Started Jitter.
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The Structured programming language

- Distributed along with Jitter as an example;
- Boring, unimaginative:
 - Pascal-style imperative language;
 - integer variables;
 - conditionals, loops;
 - recursive subprograms.
- Simple, clean implementation
 - Two VM code generators:
 - stack-based code;
 - register-based code
 - (choose with a command-line-option);
 - minimal build system example including Jitter, with Autoconf / Automake;
- Fast with little effort





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Jitter contains some assembly

I am currently supporting ELF and COFF configurations using GCC on:

- aarch64-unknown-linux-gnu
- alphaev4-unknown-linux-gnu
- alphaev67-unknown-linux-gnu
- arm-beaglebone-linux-gnueabihf
- arm-replicant-linux-androideabi (Android 6, tested on my Replicant. More recent versions probably work as well)
- m68k-unknown-linux-gnu
- mipsel-unknown-linux-gnu
- mips-unknown-linux-gnu
- powerpcle-unknown-linux-gnu

- powerpc-unknown-linux-gnu
- riscv32-unknown-linux-gnu
- riscv64-unknown-linux-gnu
- s390x-ibm-linux-gnu
- sparc64-unknown-linux-gnu
- sparc-unknown-linux-gnu
- x86_64-unknown-haiku (64-bit Haiku)
- x86_64-unknown-linux-gnu
- x86_64-w64-mingw32
- x86_64-unknown-*bsd*

Not all of these configuration are supported as efficiently as you saw, yet.

More will come.



As an alternative to what you saw in the demo the same VMs can also run as interpreters instead of JITs.

(same conditional generated code: CPP feature macros).

One of two techniques:

- direct-threading dispatch (needs goto *, even non-GCC)
- switch dispatch (just standard C)

These are slower portability fallbacks, with identical semantics to the JIT case. [Saiu, 2017] shows how they work. Extremely portable.

[If I have time: minimal-threading dispatch also exists as a middle-ground compromise between interpreter and JIT]

These alternatives exist but I will ignore them today. Today we are dealing with GNU C with GCC on a supported architecture with a supported binary format.



6/34

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6/34

Turn a generic VM instruction definition...

add VM instruction: Jitter specification

```
instruction add (?R, ?Rn 1, !R)
  code
    JITTER_ARGN2 = JITTER_ARGN0 + JITTER_ARGN1;
  end
end
```

...into every possible instantiation of register and immediate. One example:

add specialisation //n1/r4: Generated C, macroexpanded, simplified

add_r4_n1_r4_begin: _local_state.r4 = _local_state.r4 + 1; add r4 n1 r4 end:

add specialisation //n1/r4, compiled

add_r4_n1_r4_begin: addq \$1, %rdx # Here %rdx is both input and output add_r4_n1_r4_end:



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One example:

add specialisation r4/n1/r4: Generated C, macroexpanded, simplified

```
add_r4_n1_r4_begin:
    local_state.r4 = _local_state.r4 + 1;
add r4 n1 r4 end:
```

add specialisation =1/n1/r4, compiled

add_r4_n1_r4_begin: addq \$1, %rdx # Here %rdx is both input and outpu add_r4_n1_r4_end:



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 addg $1, %rdx # Here %rdx is both input and output
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Replication

(The same block of hardware instructions shown above, delimited by two labels:)

add specialisation r4/n1/r4, compiled

add_r4_n1_r4_begin: addq \$1, %rdx add_r4_n1_r4_end:

Easy: copy memory between the two labels into executable memory (allocated with mmap):

JIT-time replication: append an add/r4/n1/r4 instruction



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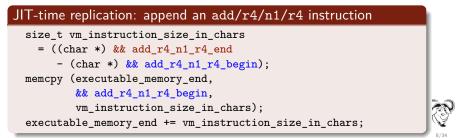
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| add VM instruction: Jitter specification |
|--|
| instruction add (?R, ?Rn 1, !R) |
| code |
| <pre>JITTER_ARGN2 = JITTER_ARGN0 + JITTER_ARGN1;</pre> |
| end |
| end |

How do we specialise add %r4, 3, %r4?

```
• As add_r4_nR_r4 ...
```

nR means that the literal number is Residual: we load into a register or memory via assembly code, filled in by the Jitter runtime.



movi \$0x3,%r120 movq %r12,%r8

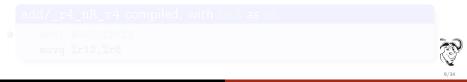


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add/_r4_nR_r4 compiled, with 0x3 as nR movl \$0x3,%r12d movq %r12,%r8

We can even have different assembly code for different kinds of constants. For example on $x86_64$ the literal 0x0 can be loaded in a more efficient way than other numbers.

add/_r4_nR_r4 compiled, with 0x0 as n

xorl %r12d,%r12d # This only works for 0x0
movq %r12,%r8

Same for small constants on most RISCs.

(A hardware register has been reserved)

This is very architecture-specific, and a little laborious, but...



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Fast branches (1/1)

How do we perform jumps from a VM instruction to another?

• One way would be by materialisation:

That works (Jitter used to do that) but is inefficient.

• Much better solution: generate something like

b \$f compiled, with \$2 being patched in jmp .L # .L will be overwritten after replication



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There are two main problems:

- How to present this to the user in a friendly way?
 - JITTER_BRANCH_FAST(label), JITTER_BRANCH_FAST_IF_NONZERO(expression, label) JITTER_PLUS_BRANCH_FAST_IF_OVERFLOW(lvalue, rvalue, rvalue, label)...
- How to implement this (where to patch)?
 - We need a new idea: patch-ins.

[Quick demo with uninspired

[unless I am very late] - conditional branch - plus-or-branch-if-overflow



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[unless I am very late]

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Patch-ins

The fast-branching macro expands to something like:

This trick uses subsections. A pointer to the memory to patch is stored in a global table; the displacement between that address and an instruction start address is a literal constant.



C restrictions: global variables/constants (ex.: string literals)

C globals are accessed with PC-relative instructions on modern architectures.

- a_global
 ⇒ (* _a_local_struct->a_global_address)
 wrapping mechanism:
 - (* a local struct->a global addr

Jitter specification

wrapped-globals
 my_datum
 prompt_string
end



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a_global
>> (* _a_local_struct->a_global_address)
wrapping mechanism: #define a_global \

(* _a_local_struct->a_global_address)

Jitter specification

wrapped-globals my_datum prompt_string end



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a_global
>> (* _a_local_struct->a_global_address)
wrapping mechanism:
#define a global \

(* _a_local_struct->a_global_address)

Jitter specification

wrapped-globals
 my_datum
 prompt_string
end



Functions are also accessed with PC-relative instructions. Same trick necessary...

- a_function
 - \implies (* _a_local_struct->a_function_address)
- wrapping mechanism:
 - #define a function
 - (* _a_local_struct->a_function_address)

Jitter specification

wrapped-functions

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get

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On some architectures / ABIs calling a C function clobbers CPU state: for example the global pointer register on Alpha, or a floating point status register on SH4. [If I have time: violating the C ABI with respect

- A wrapped function call should expand to an expression "like": ({ PRE_PROCEDURE_CALL_CODE;
 - int _res \leftarrow any output type, not just
 - = (* _a_local_struct->a_function_address) (args);
 POST_PROCEDURE_CALL_CODE;
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- The macro must work with any arity, any input type, any output type and votid is special.
- The actual definition is complex and requires GNU/C (but is well factored).



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- The actual definition is complex and requires GNU C (but is well factored).



- The actual macro needs:
 - statement-expressions;
 - typeof;
 - __builtin_choose_expr;
 - __builtin_types_compatible_p;
 - different definition for functions returning void.

```
For more information use git grep 'Function wrapping'
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Jitter specification

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wrapped-functions
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- VM instruction code blocks require care:
 - write C...
 - ... think assembly
- No restrictions in called C functions;
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What we have learned up to this point:

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Luca Saiu

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What can *really* go wrong

GCC can compile C in ways that are legitimate, but break our strategy of copying and recombining hardware instruction blocks.

- reorder;
- tail-merging;
- inconsistent register assignments across branches;
- far branches;
- PC-relative loads to materialise constants.



Jitter Low-level view C restrictions Playing with fire Closing Reorder Tail merging RA across branches Hints at the rest

What can go wrong: reorder (1/2): the problem)

When replicating we memcpy from the beginning to the end:



But GCC might (legitimately) reorder blocks:



Code from different VM instructions may even be intertwin

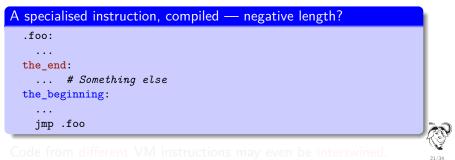
21/34 BTS 2022 Jitter Low-level view C restrictions Playing with fire Closing Reorder Tail merging RA across branches Hints at the rest

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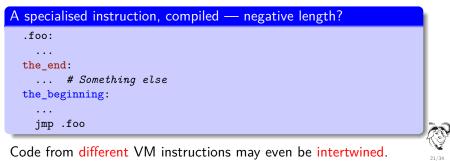


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The generated file *umprefix*-vm2.c **must** be compiled with -fno-reorder-blocks.

This GCC optimisation option is necessary for correctness!

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Two VM instructions happen to behave the same way at the end:

| foo VM instruction | |
|---------------------------|--|
| <pre>foo_beginning:</pre> | |
| ••• | |
| xxx | |
| yyy | |
| foo_end: | |

| oar VM instruction |
|--------------------|
| bar_beginning: |
| |
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| yyy |
| bar_end: |



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 foo_beginning:

 ...

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 foo_end:

Or GCC might (legitimately) compile foo and bar factoring their common tail:

```
...
jmp .tail_of_foo # Hmm...
bar_end: # If at all
```

After copying, at run time, the jump will reach **out of** the relocated bar_beginning and bar_end.



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Crash. (If you are lucky.)



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GCC has a -fno-tail-merge option...

... which is, unfortunately, **not enough**: GCC merges some tails even with the option. [Changing GCC now would not be very useful in practice: many stable releases with this behaviour are in use]

We need a more creative solution.



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What can go wrong: tail merging (3/3): the solution)

Use GNU C assembly constraints to pretend there are dependencies, and that a variable is modified in many different ways: prevent factoring by making tails appear different.

foo VM instruction, in C

```
foo_beginning:
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The variable must actually be used.

The Array's base is in a reserved register: the obvious candidate, but I am not speaking of The Array in this presentation]



A lot of Jitter code is based on this trick: lie to the compiler

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foo_beginning:
...
asm (: "+X" (variable),
    "# Useless 123");
foo_end:
asm (: "+X" (variable),
    "# Useless 124");
goto * variable;
```

| bar VM instruction, in C |
|--------------------------|
| bar_beginning: |
| |
| asm (: "+X" (variable), |
| "# Useless 125"); |
| bar_end: |
| asm (: "+X" (variable), |
| "# Useless 126"); |
| goto * variable; |

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BTS 2022

Can we guarantee that GCC uses the same register assignment at a branch site and at the target site?

the target is always the beginning of a VM instruction

```
compiled code going to Ltaryget
jmp .Ltemp
...
.Ltemp:
mov ..., %rdx # Register assignment now compatible with Ltarget
jmp Ltarget
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Far branches

[There is no time for this]

However, if you know about the problem (for example it is inescapable when generating code for SH4), you also know the solution: indirect jumps. Here with Jitter the solution is still the obvious one — I will just need to implement it.

This is not done yet. I will, as it is important in practice on every architecture except m68k, i386 and x86_64.



PC-relative loads to materialise constants

[There will be no time for this]

"Luckily" there is no real solution either (that I know of) so you are not missing much.



- Good architecture-dependent support is complicated
- Possibly unjustified effort for a single VM
- It will not happen unless the author enjoys assembly and low-level programming
- Architecture-dependent, VM-independent
- Jitter is the right way to factor
 - Jitter users do not need to play with fire
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Is this the right thing?

Is this complexity necessary?

- In an ideal world a VM generator would be simpler.
- Jitter is a product of its environment;
 - Jitter's complexity comes from the lack of flexibility of C;
 Impossible to reuse a C compiler without playing with fire, if we want to keep performance.
- Is the environment complexity necessary?
 - Unix is too complex;
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Any questions?



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http://ageinghacker.net GNU Jitter and GCC: the fun of playing with fire BTS 2022



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