GNU Jitter and the illusion of simplicity

or

Copying, patching and combining compiler-generated code in executable memory

or

The Anarchist’s guide to GCC

or

The fun of playing with fire

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GNU Project

Binary T00ls Summit 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](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](http://ageinghacker.net/bts2022/jitter-0.9.285.tar.gz)

- Git source repository [http://git.ageinghacker.net/jitter](http://git.ageinghacker.net/jitter), requiring bootstrap with the Autotools plus Flex, GNU Bison, GNU Texinfo and so on. Use the tag `binary-tools-summit-2022` to get today's version.
History and rationale

- 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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Demo: 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**

---

**Demo**

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**Demo**
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.
Simple dispatches and why we are ignoring them

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.
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Specialisation

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 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 r4/n1/r4, compiled**

```
add_r4_n1_r4_begin:
    addq $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

    size_t vm_instruction_size_in_chars
        = ((char *) && add_r4_n1_r4_end
            - (char *) && add_r4_n1_r4_begin);
    memcpy (executable_memory_end, && add_r4_n1_r4_begin,
            vm_instruction_size_in_chars);
    executable_memory_end += vm_instruction_size_in_chars;
```
Replication

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```
Literal materialisation (1/2)

add VM instruction: Jitter specification

```
instruction add (?R, ?Rn 1, !R)

code
    JITTER_ARGN2 = JITTER_ARGNO + JITTER_ARGN1;
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.

```
add/_r4_nR_r4 compiled, with 0x3 as nR

  movl $0x3,%r12d
  movq %r12,%r8
```

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BTS 2022
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```assembly
add/_r4_nR_r4 compiled, with 0x3 as nR
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- `movl $0x3,%r12d`
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```
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 nR
    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...

... VM-independent: the complexity is all in Jitter!
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```plaintext
add/_r4_nR_r4 compiled, with 0x0 as nR
  xorl %r12d,%r12d  # This only works for 0x0
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How do we perform jumps from a VM instruction to another?

- One way would be by materialisation:
  - load the target address into a register
  - jump via register

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

- Much better solution: generate something like

```
b $f compiled, with $f 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]
Fast branches (2/2)

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    JITTER_PLUS_BRANCH_FAST_IF_OVERFLOW(lvalue, rvalue, rvalue, label) ...`

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[Quick demo with uninspired
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- conditional branch
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The fast-branching macro expands to something like:

(Macro-expanded) GNU C, simplified

```
asm goto (.pushsection .data, 42
"  .quad hole_to_fill_%=%=
"  .quad " SPECIALIZED_INSTRUCTION_ID 
"  .quad " PATCH_IN_CASE 
".popsection
"hole_to_fill_%=%=
"  .skip " ROUTINE_LENGTH_IN_BYTES 
: : /* inputs... */
: : unreachable_label_jumping_where_gcc_cant_know);
```

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**
  \[ \Rightarrow (* \_a\_local\_struct->a\_global\_address) \]

- wrapping mechanism:
  ```
  #define a_global \n  (* \_a\_local\_struct->a\_global\_address)
  ```
C globals are accessed with **PC-relative** instructions on modern architectures.

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  \[
  \Rightarrow (\_a\_local\_struct->a\_global\_address)
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- wrapping mechanism:
  
  ```
  #define a_global \n  (\_a\_local\_struct->a\_global\_address)
  ```

---

**Jitter specification**

```ruby
wrapped-globals
  my_datum
  prompt_string
end
```
C globals are accessed with **PC-relative** instructions on modern architectures.

- **a_global**
  \[
  \rightarrow (* _a_local_struct->a_global_address)
  \]

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

**Jitter specification**

```jitter
wrapped-globals
  my_datum
  prompt_string
end
```
Functions are also accessed with **PC-relative** instructions.

Same trick necessary...

```c
  a_function
  ⇒ (* _a_local_struct->a_function_address)
```

**wrapping mechanism:**
```
#define a_function
  (* _a_local_struct->a_function_address)
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**Jitter specification**
```
wrapped-functions
  putc
  getc
end
```

…but this is not enough!
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  ```

**Jitter specification**

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- \texttt{a\_function}
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  ```
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---

### Jitter specification

```plaintext
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  putc
getc
end
```

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Functions are also accessed with \textbf{PC-relative} instructions. Same trick necessary...

\begin{itemize}
  \item \texttt{a\_function}
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\textbf{Jitter specification}

\begin{verbatim}
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\ldots but this is \textbf{not enough}!
C restrictions: calling C functions (2/3)

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 to call-clobbered registers can be useful]

- A wrapped function call should expand to an expression “like”:

  ```
  ({ PRE_PROCEDURE_CALL_CODE;
  int _res = any_output_type_not_just_int
  = (* _a_local_struct->a_function_address) (args);
  POST_PROCEDURE_CALL_CODE;
  _res; })
  ```

- The macro must work with any arity, any input type, any output type — and void is special.

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

Still very easy to use:

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C operators implemented as out-of-line routines

Very architecture-dependent:

- Sometimes solvable by command-line options.
- Ex.: struct assignment on PowerPC: `-mblock-move-inline-limit=8192`
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- GCC/Cinter does not know why it wants to inline.

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

When replicating we `memcpy` from `the_beginning` to `the_end`:

```
A specialised instruction, compiled

the_beginning:
...
...
the_end:
```

But GCC might (legitimately) reorder blocks:

```
A specialised instruction, compiled — negative length?

.foo:
...
...
.the_end:
...
# Something else
.the_beginning:
...
jmp .foo
```

Code from different VM instructions may even be intertwined.
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Code from different VM instructions may even be intertwined.
In this case the solution is easy: GCC has a `-fno-reorder-blocks` option.

The generated file `vmprefix-vm2.c` must be compiled with `-fno-reorder-blocks`.

This GCC optimisation option is necessary for correctness!

`JITTER_CFLAGS` contains it.

(Out of defensiveness, VM code checks at startup that specialised instruction blocks are disjoint and sizes are non-negative.)
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What can go wrong: tail merging (1/3: the problem)

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

**foo VM instruction**

```plaintext
foo_beginning:
...
xxx
yyy
foo_end:
```

**bar VM instruction**

```plaintext
bar_beginning:
...
xxx
yyy
bar_end:
```

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

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```plaintext
foo_beginning:
...
.tail_of_foo:
xxx
yyy
foo_end:
```

**bar VM instruction**

```plaintext
bar_beginning:
...
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.
Crash. (If you are lucky.)
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<td>...</td>
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</tr>
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After copying, at run time, the jump will reach out of the relocated `bar` beginning and `bar`.end.
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GCC has a \texttt{-fno-tail-merge} option...

...which is, unfortunately, \textbf{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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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.

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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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.

```c
foo VM instruction, in C
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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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:
    ...
    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;
```

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!
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.

```asm
jmp .Ltemp
...
.Ltemp:
mov ..., %rdx # Register assignment now compatible with Ltarget
jmp Ltarget
```

[There is no time for the details: the solution uses `asm goto` in a creative way, lying to the compiler]
Register-assignments across branches

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

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jmp .Ltemp
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**compiled code going to Ltarget**

GCC can (legitimately) generate code like this:

```
jmp .Ltemp
...
.Ltemp:
  mov ..., %rdx # Register assignment now compatible with Ltarget
jmp Ltarget
```

[There is no time for the details: the solution uses `asm goto` in a creative way, lying to the compiler]
Register-assignments across branches

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```plaintext
compiled code going to Ltarget

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.Ltemp:
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[There is no time for the details: the solution uses *asm goto* in a creative way, lying to the compiler]
[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.
[There will be no time for this]

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

- 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
    - (Notice that I do)
  - Architecture-dependent, VM-independent
- Jitter is the right way to factor
  - Jitter users do not need to play with fire
  - Jittery VMs are high-level
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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;
- C is too complex.
- We should be prepared to restart from scratch.
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- We should be prepared to restart from scratch
  - Factor. Simplify. **Reject compatibility.**
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- Jitter Texinfo documentation (⇒ Info, PDF, HTML, …):
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  - Jitter example manuals:
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Luca Saiu
http://ageinghacker.net
GNU Jitter and GCC: the fun of playing with fire
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Thanks.

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