Security Enhanced LLVM

Jeremy Bennett

Why?

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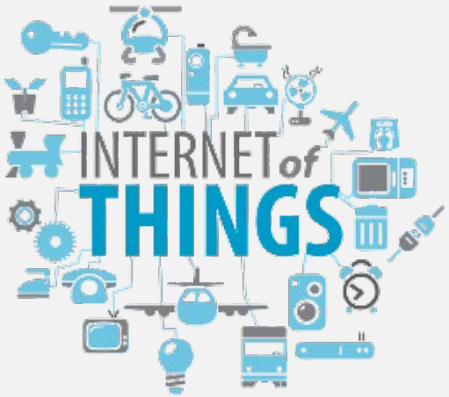
Why?



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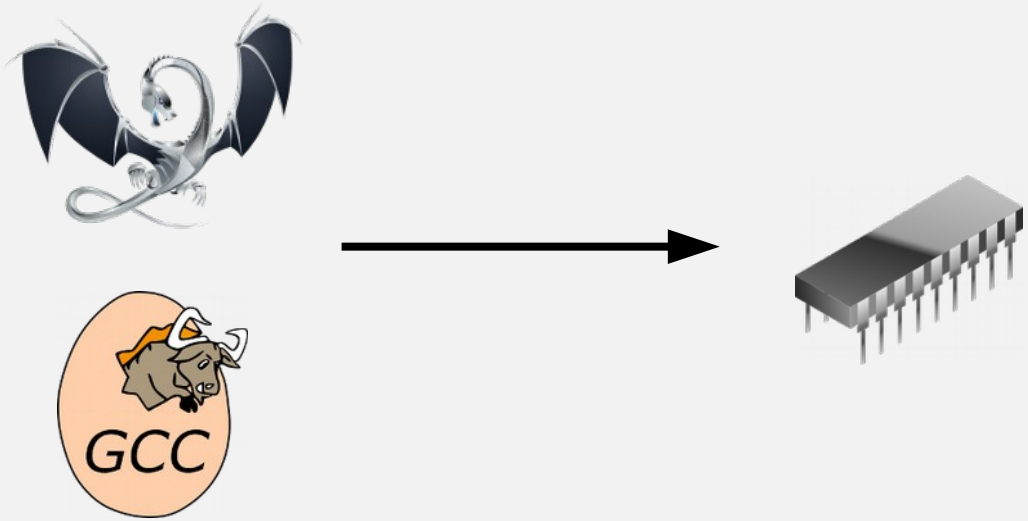
Why the Compiler?



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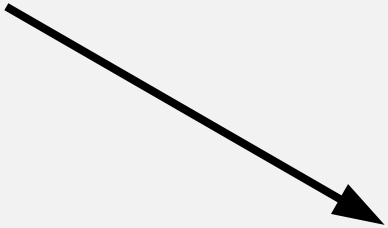
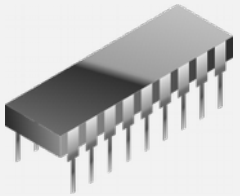
Why the Compiler?

C/C++





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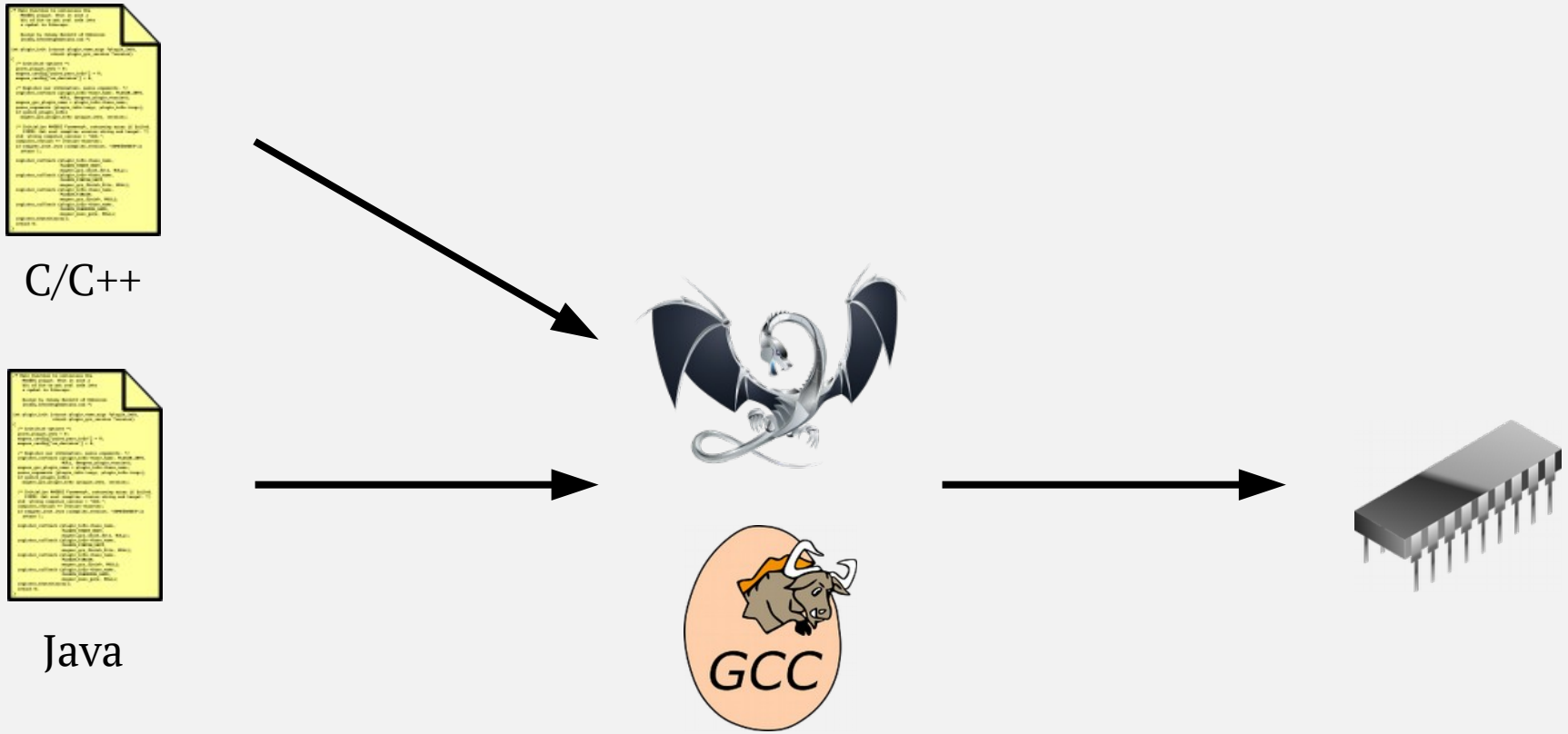

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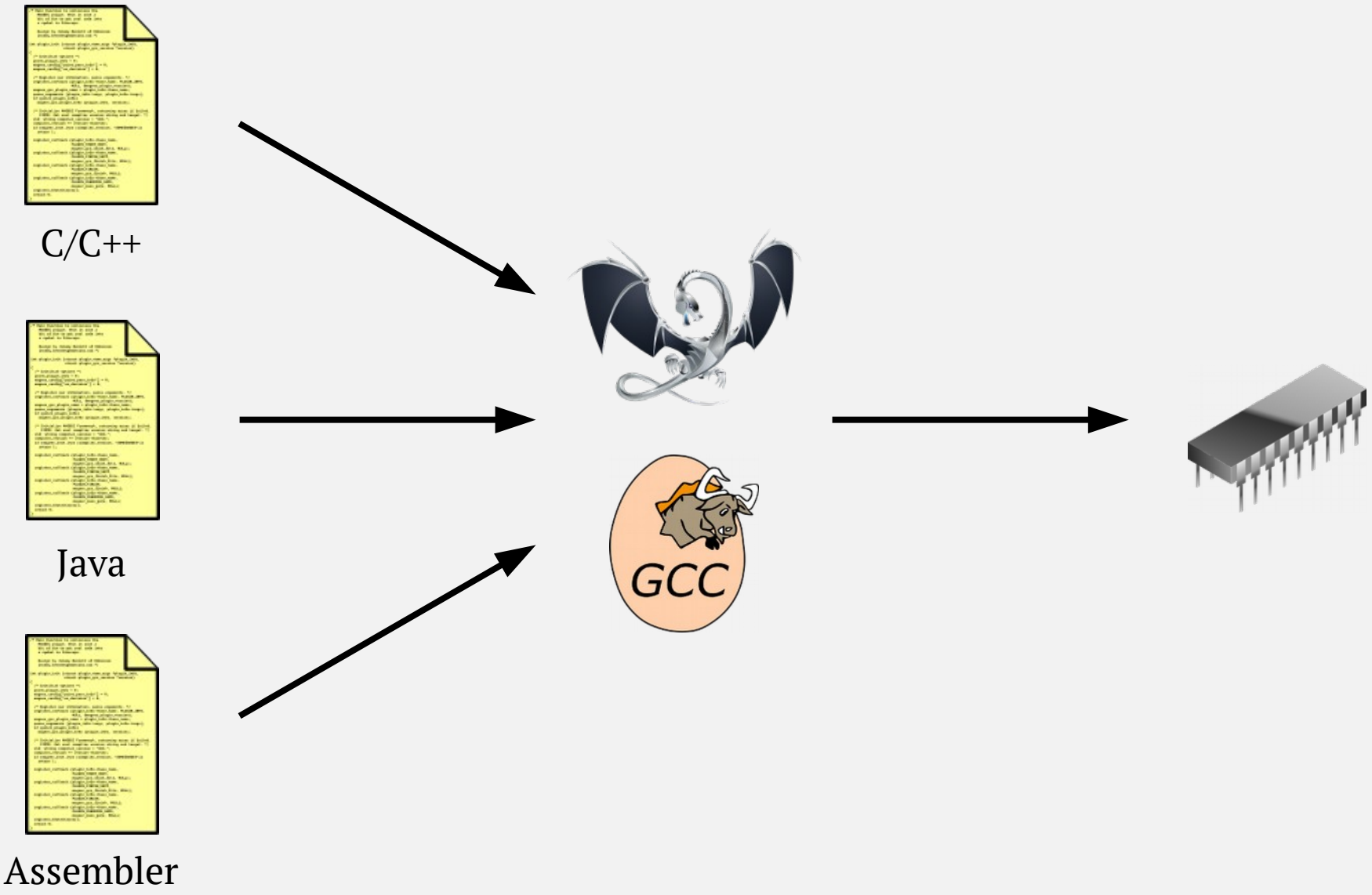

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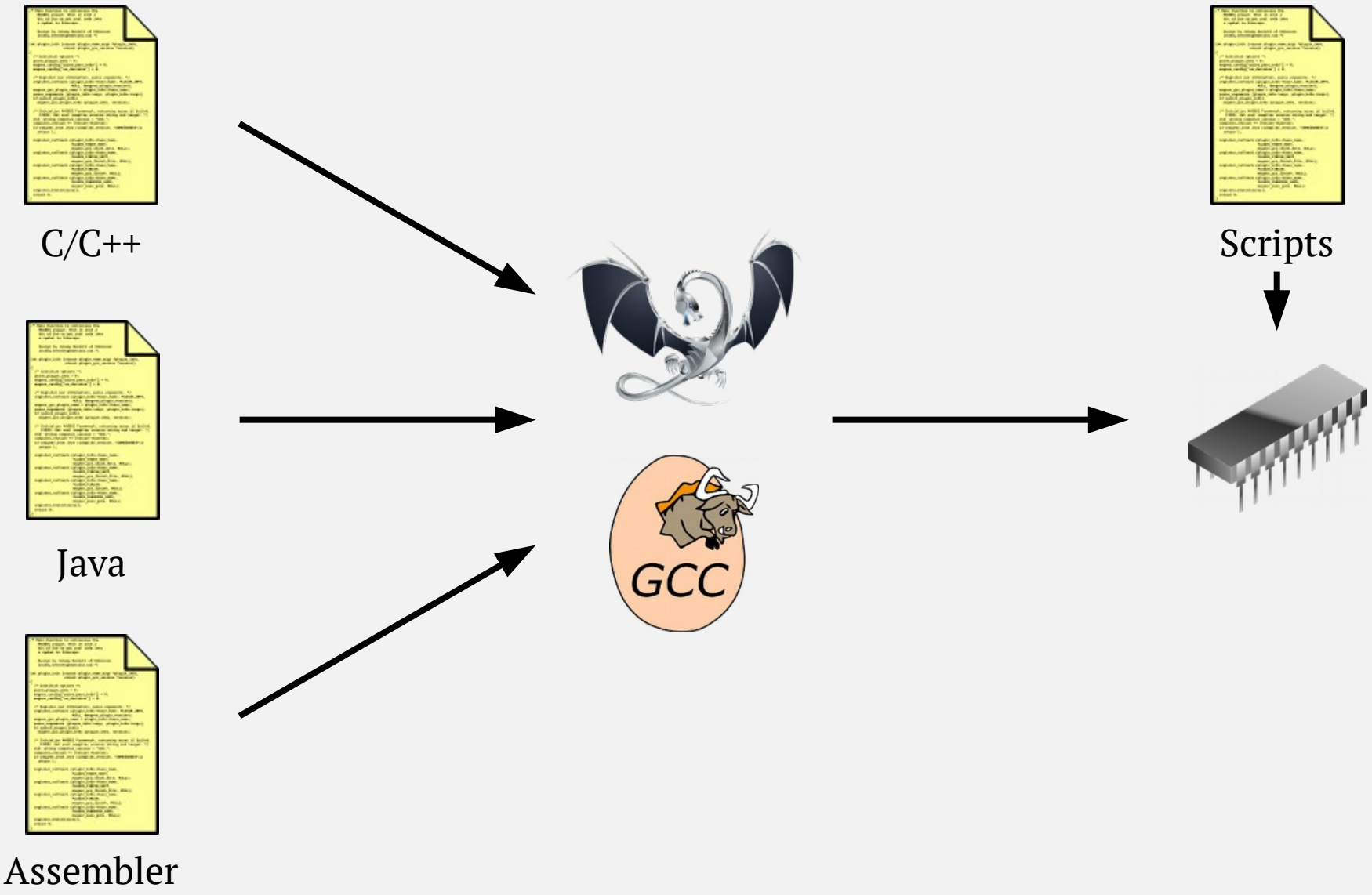

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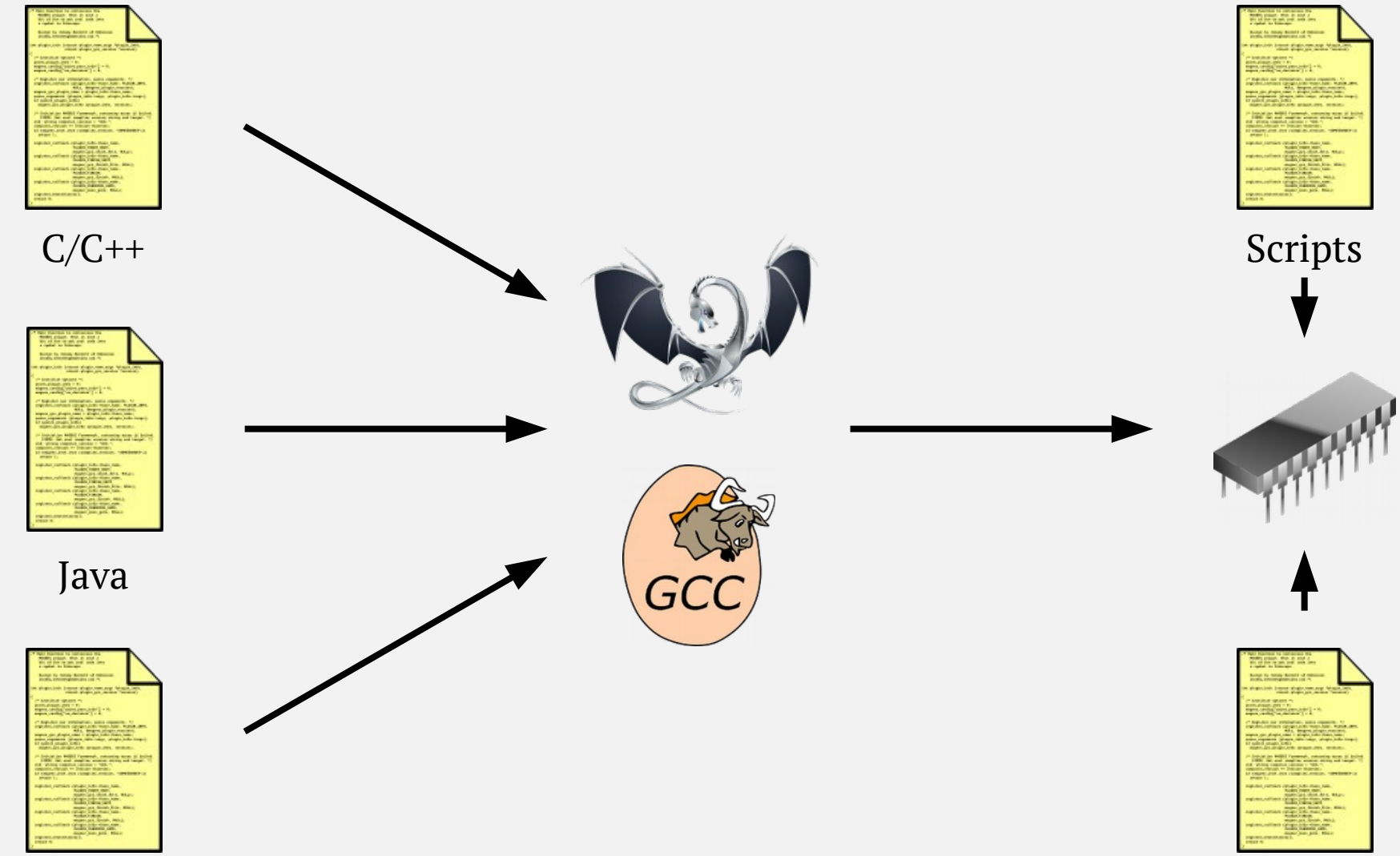

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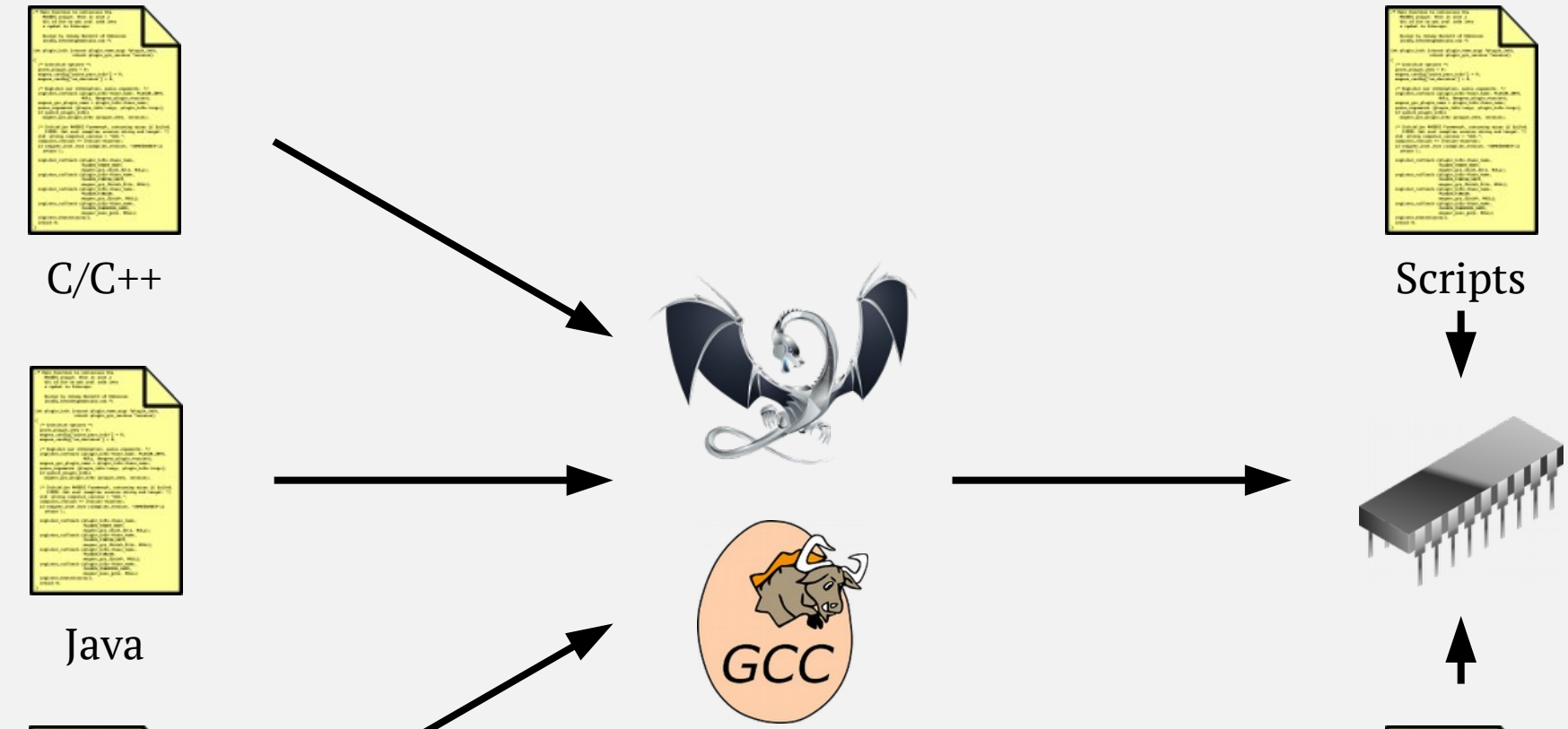

The compiler gets to look at (almost) all the code

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How The Compiler Can Help

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Warning of bad practice

Advising the programmer when code appears to follow bad practice

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How The Compiler Can Help

Warning of bad practice

Advising the programmer when code appears to follow bad practice

Providing heavy lifting

Automating complex tasks to make them easier for the programmer

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Using LLVM to guarantee program integrity
LLVM Dev Meeting, Nov 2016

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Previously...

Using LLVM to guarantee program integrity
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- Hardware adds support for:
  - instruction integrity
  - control flow integrity

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Previously...

Using LLVM to guarantee program integrity
LLVM Dev Meeting, Nov 2016

- Hardware adds support for:
  - instruction integrity
  - control flow integrity
- LLVM adds `__attribute__ ((protected))`

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Simple Things

```
int mangle (uint32_t k)
{
  uint32_t  res = 0;
  int i;

  for (i = 0; i < 8; i++)
   {
      uint32_t b = k >> (i * 4) & 0xf;
      res |= b << ((7 - i) * 4);
   }
  return res;
}

int main (int argc,
          char *argv[])
{
  uint32_t km;
  km = mangle (atoi (argv[1]));
  return (&km)[2];
}
```

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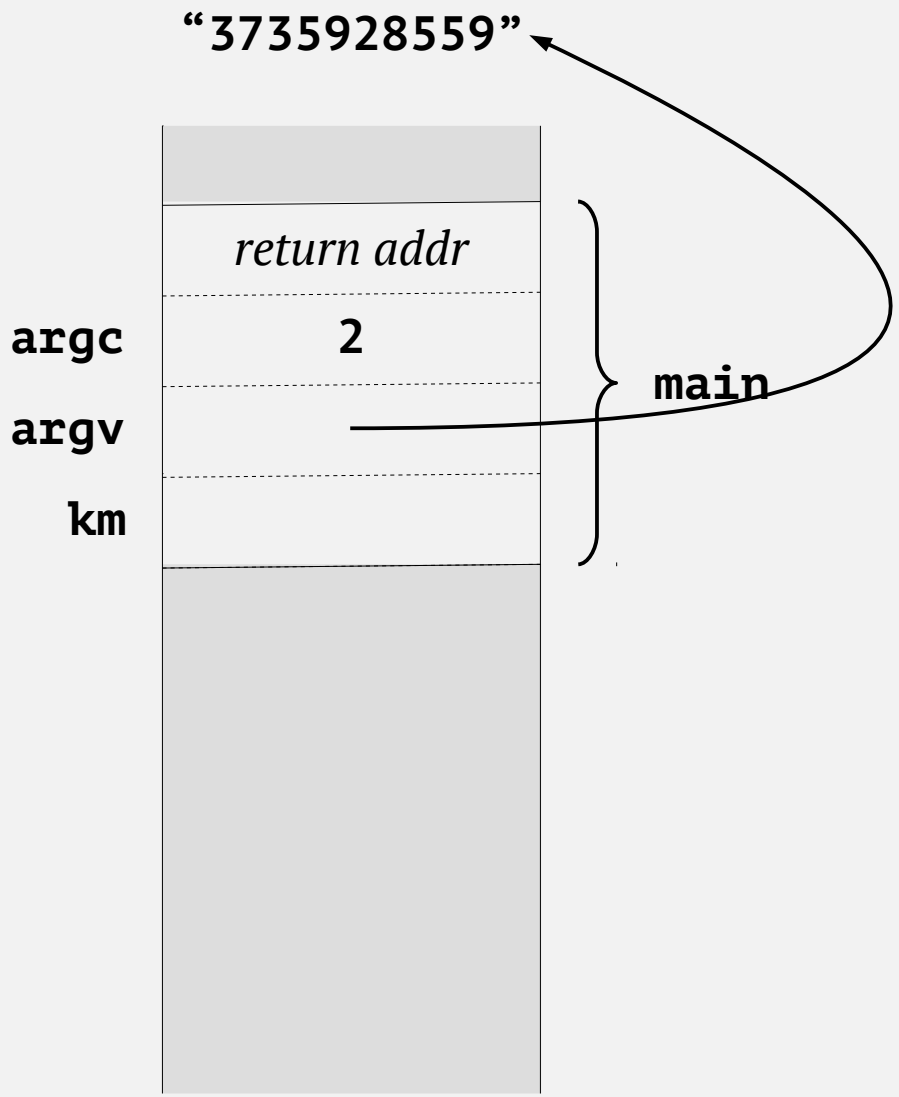

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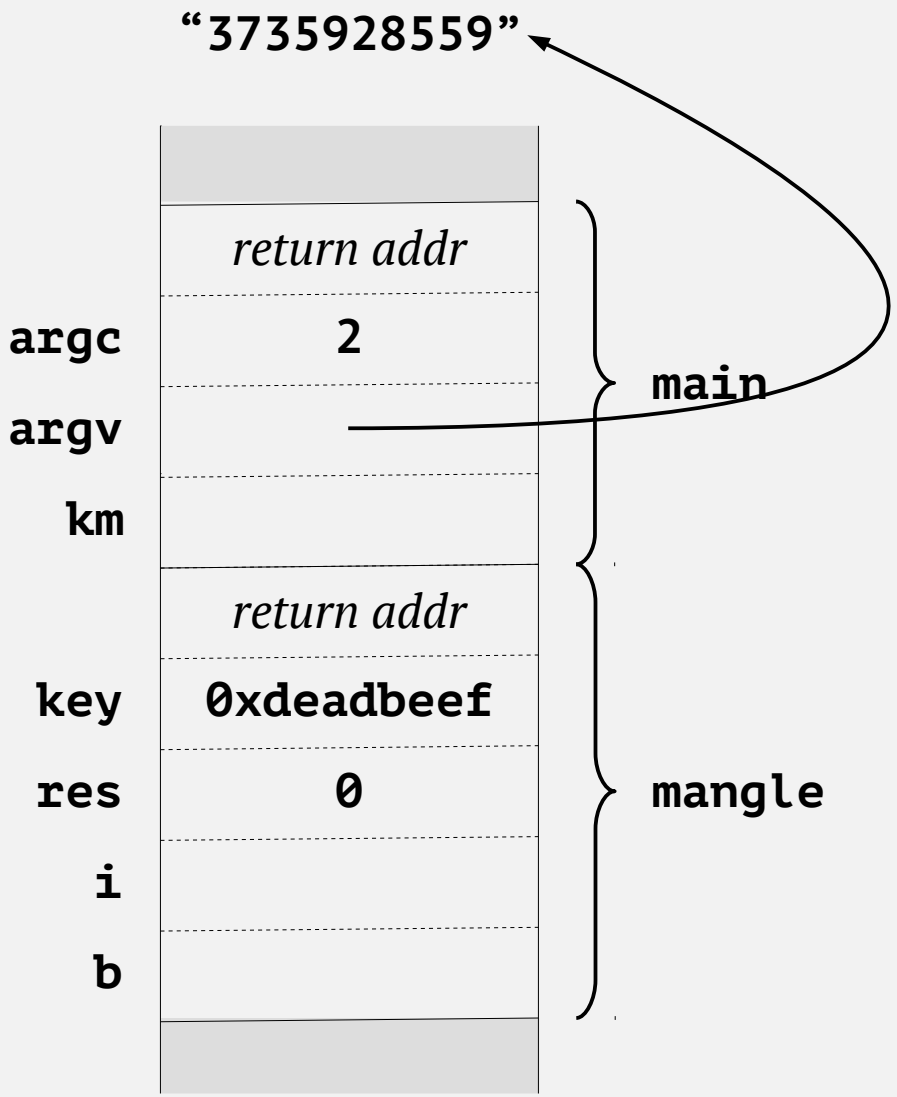

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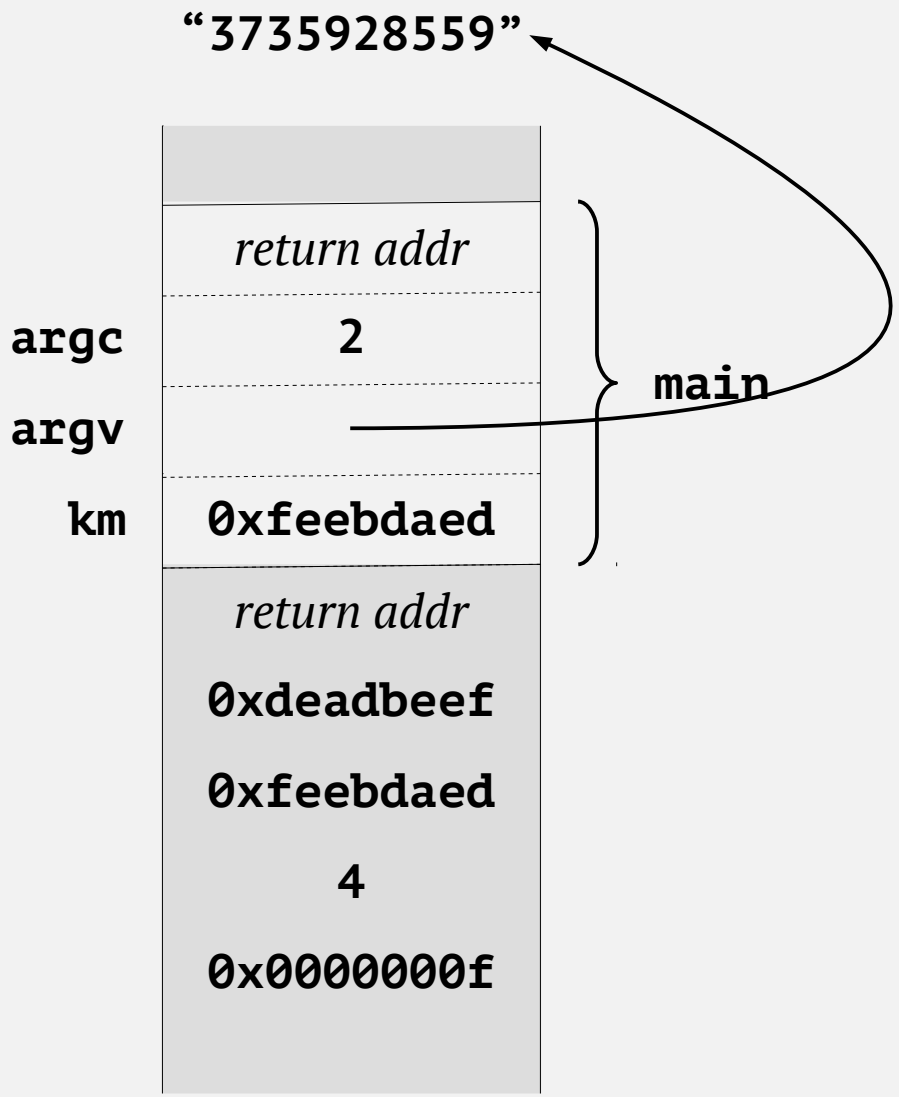

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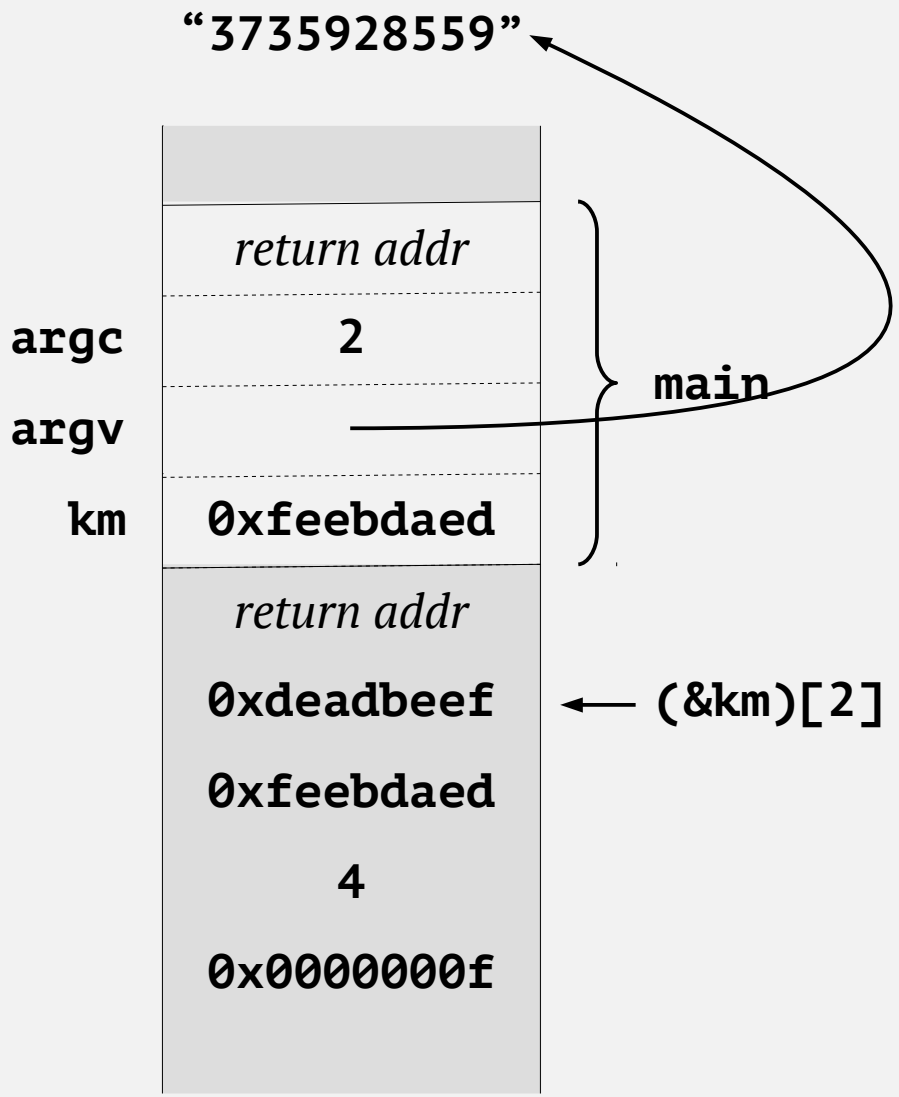

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Simple Fix

```
int mangle (uint32_t k)
  __attribute__ ((erase_stack))
{
  uint32_t  res = 0;
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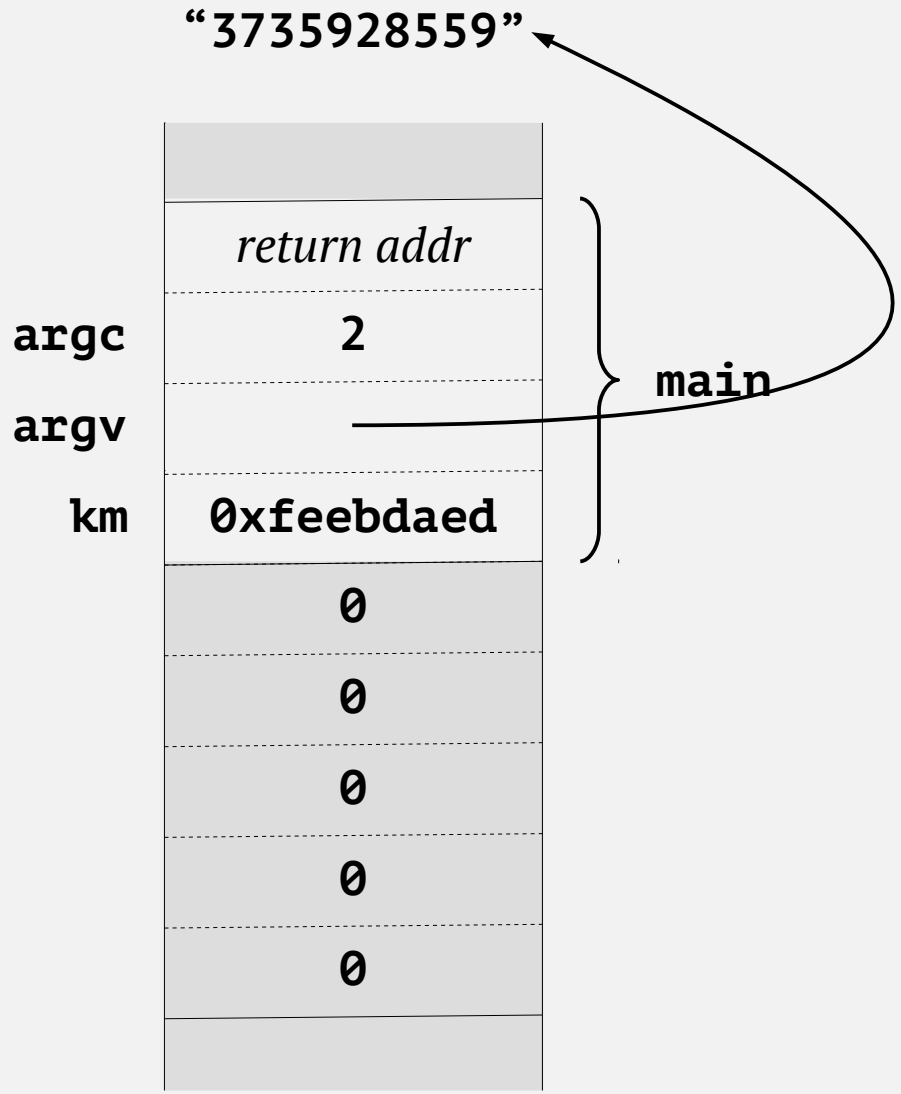

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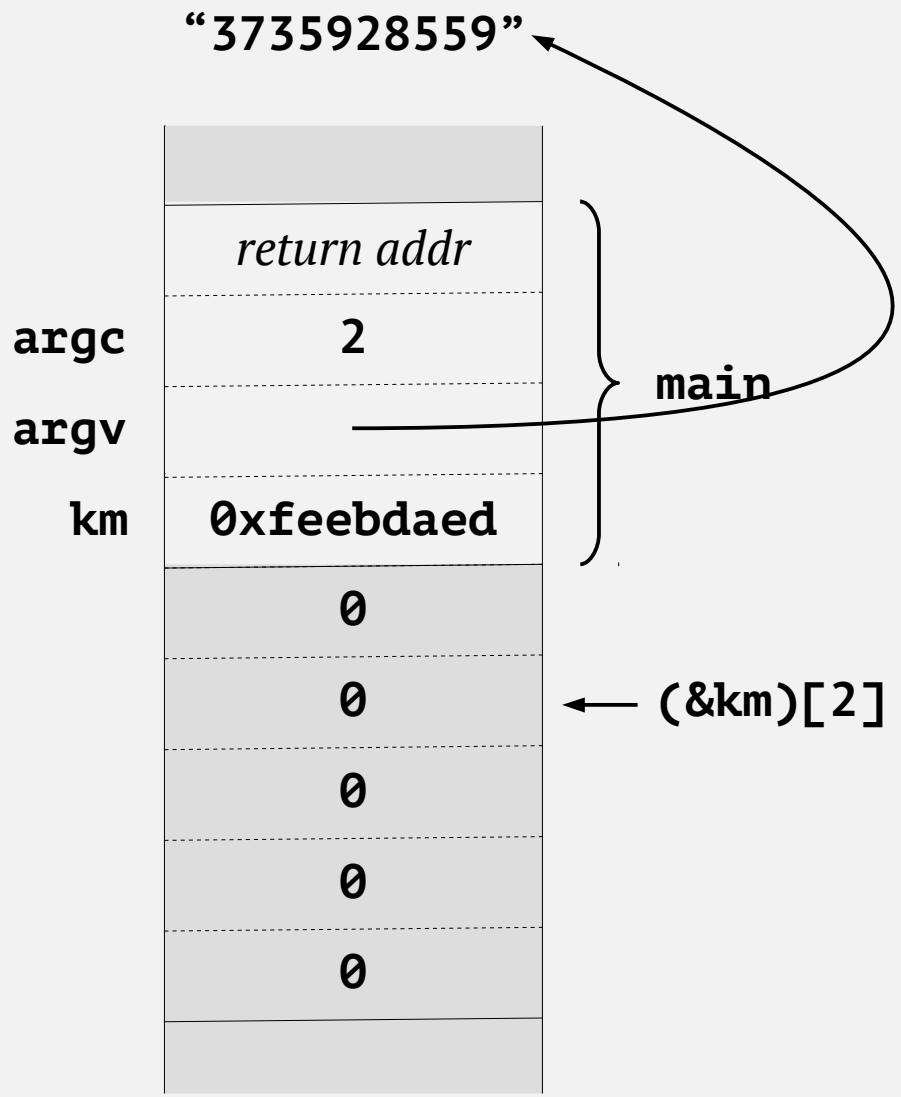

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A Better Simple Fix

```
int mangle (uint32_t k)
  __attribute__ ((erase_stack (0xaa)))
{
  uint32_t  res = 0;
  int i;

  for (i = 0; i < 8; i++)
   {
      uint32_t b = k >> (i * 4) & 0xf;
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   }
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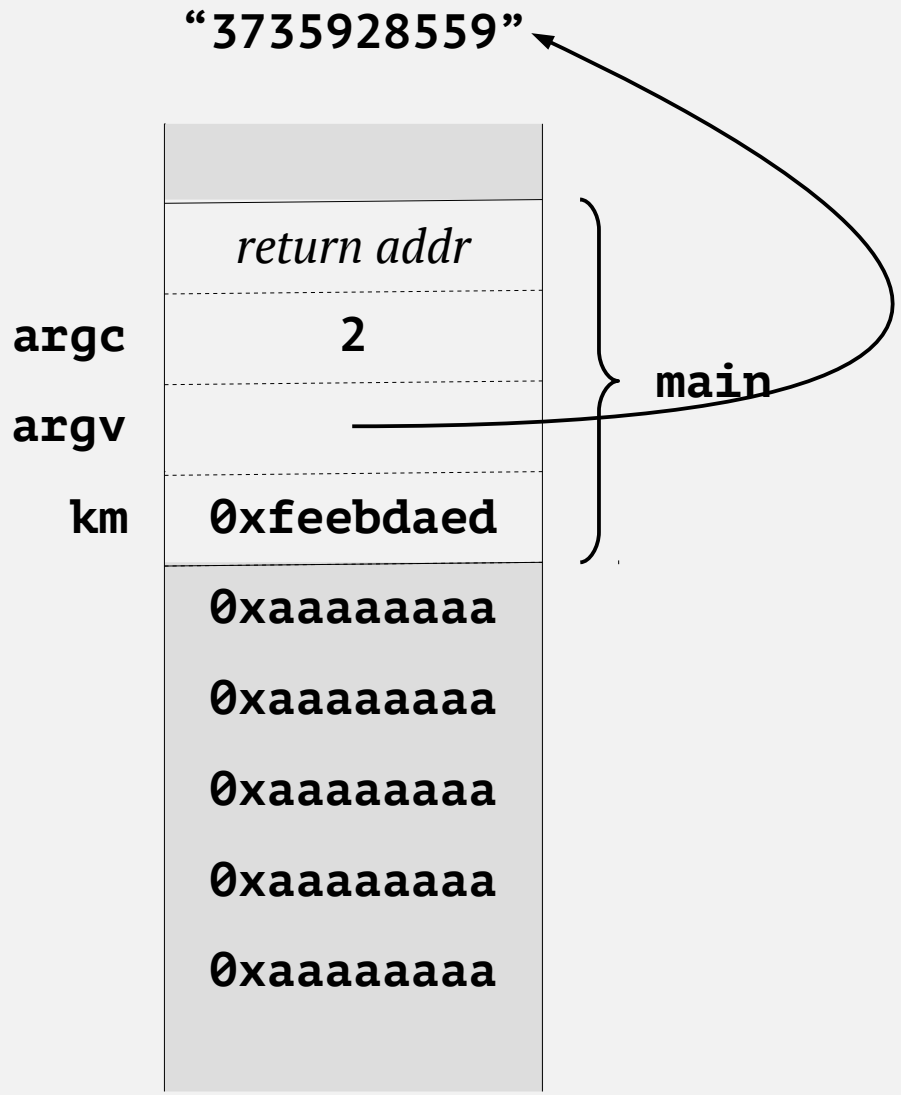

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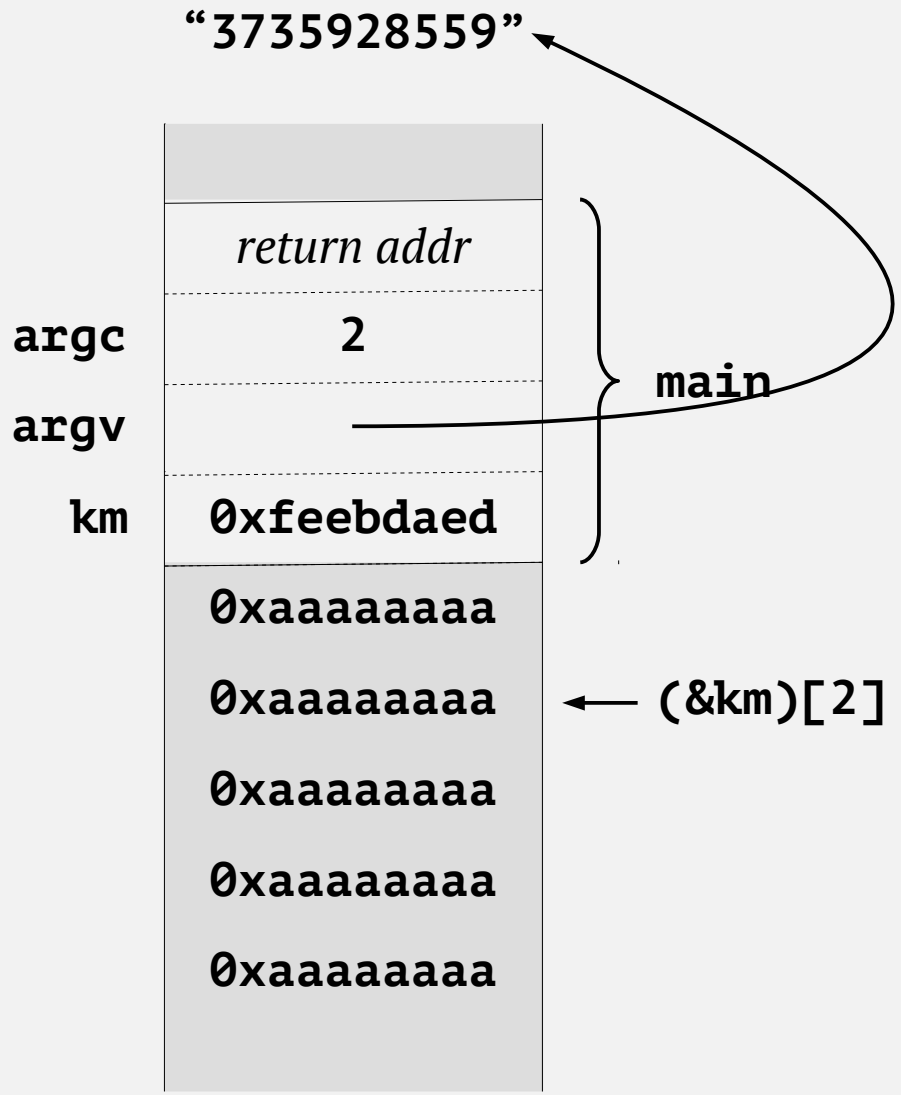

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The Best Simple Fix?

```
int mangle (uint32_t k)
  __attribute__ ((randomize_stack))
{
  uint32_t  res = 0;
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  for (i = 0; i < 8; i++)
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   }
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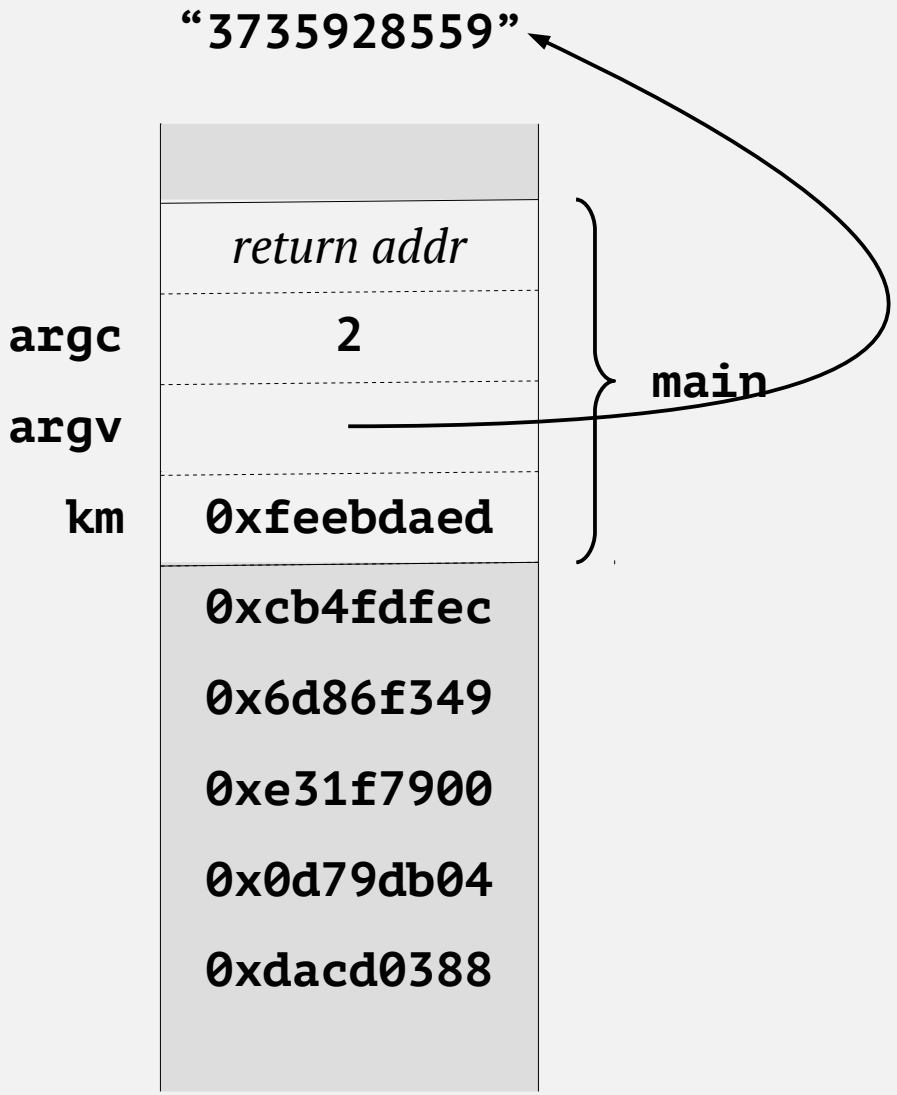

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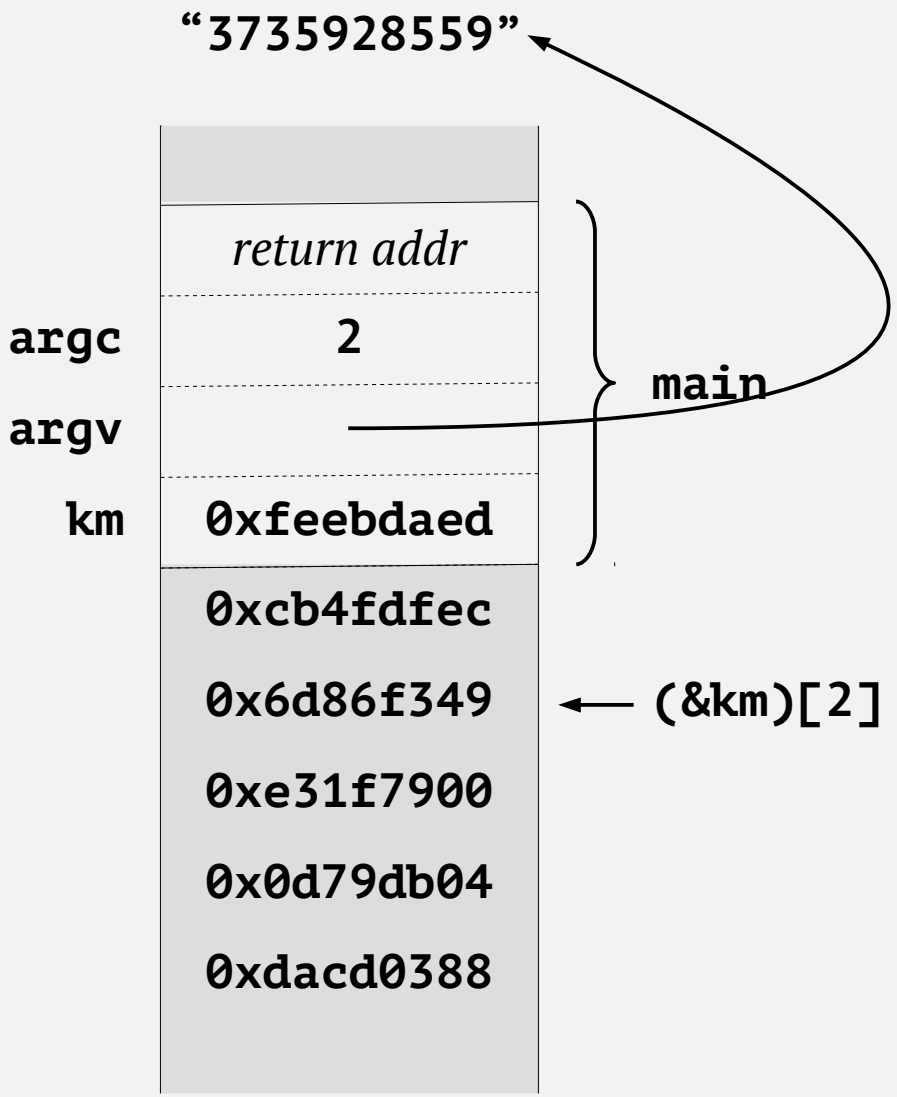

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Fixing setjmp/longjmp

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Fixing setjmp/longjmp

```
int top_func ()
{
  ...
  setjmp (buf)
  ...
}

int midfunc (uint32_t  k,
             jmp_buf *buf)
{
  ...
}

int farfunc (jmp_buf *buf)
{
  ...
  longjmp (*buf, 42);
}
```

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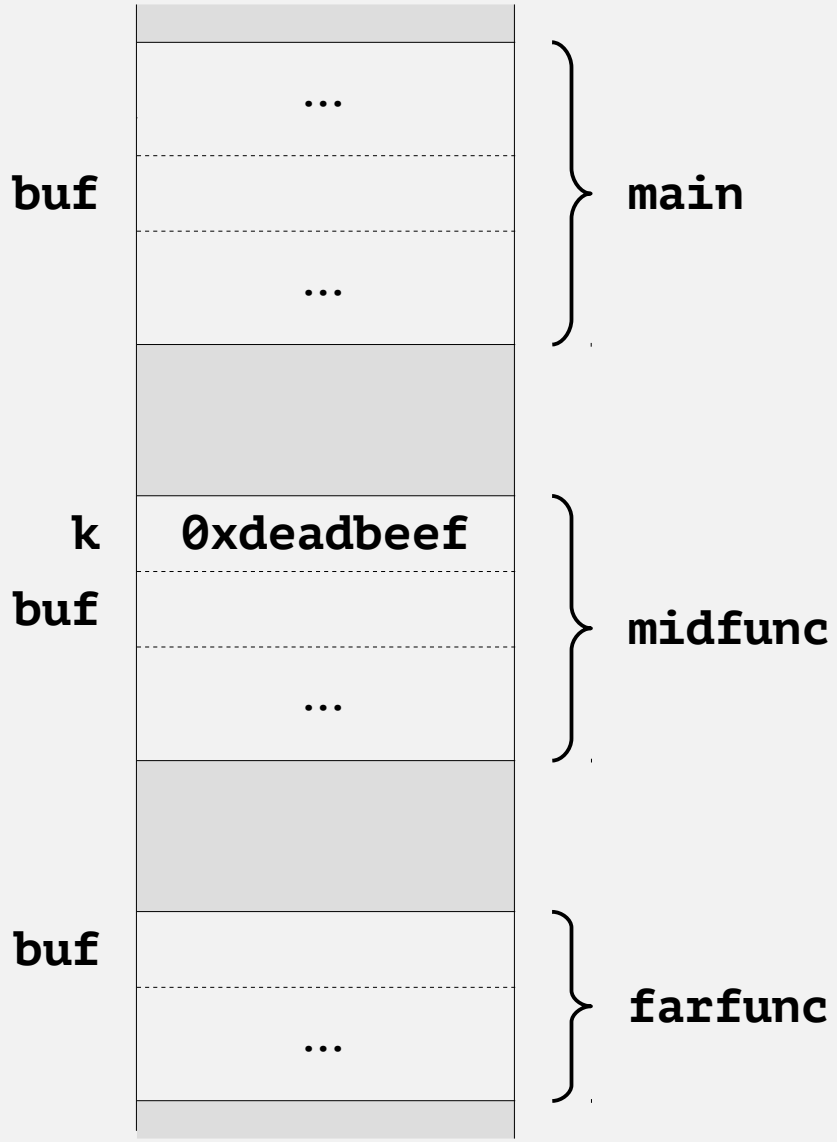

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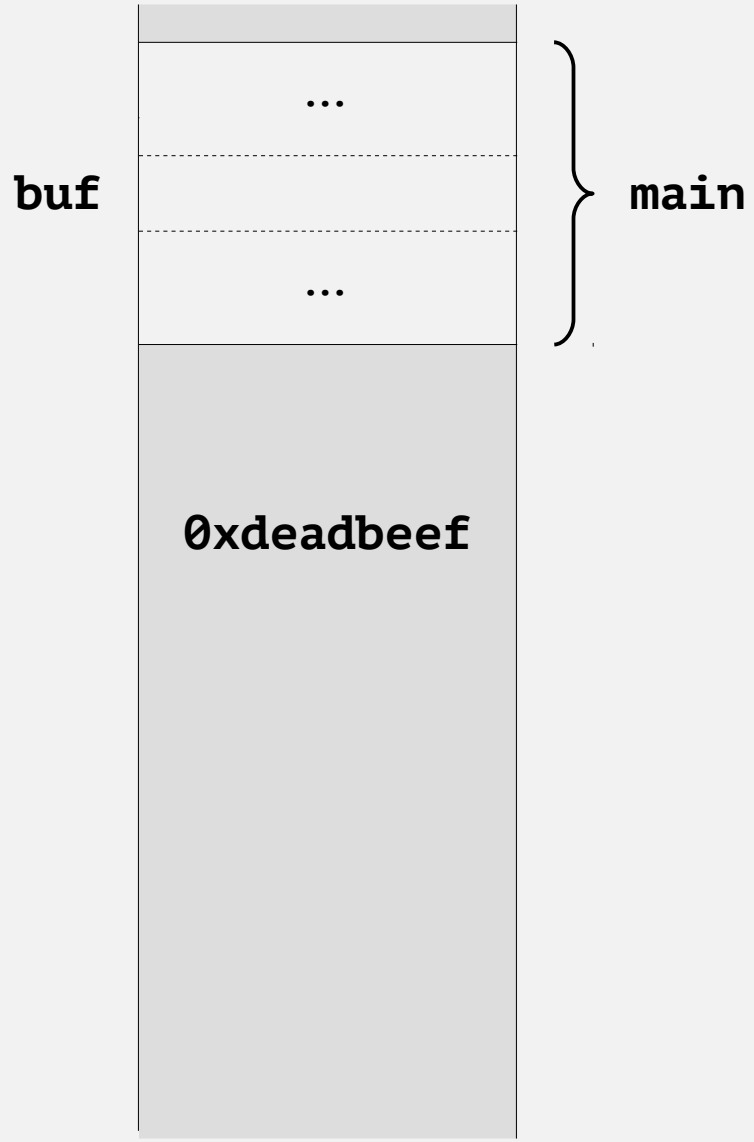

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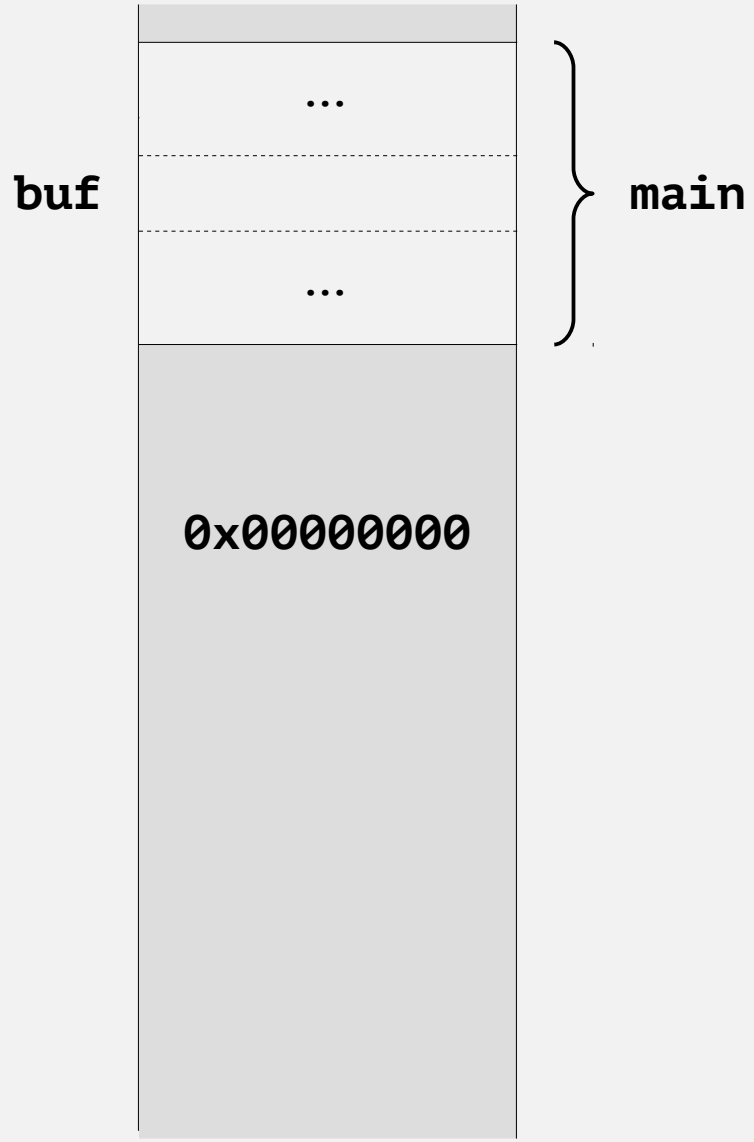
clang -ferase-stack ...



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Fixing setjmp/longjmp

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  ...
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{
  ...
  longjmp (*buf, 42);
}
```
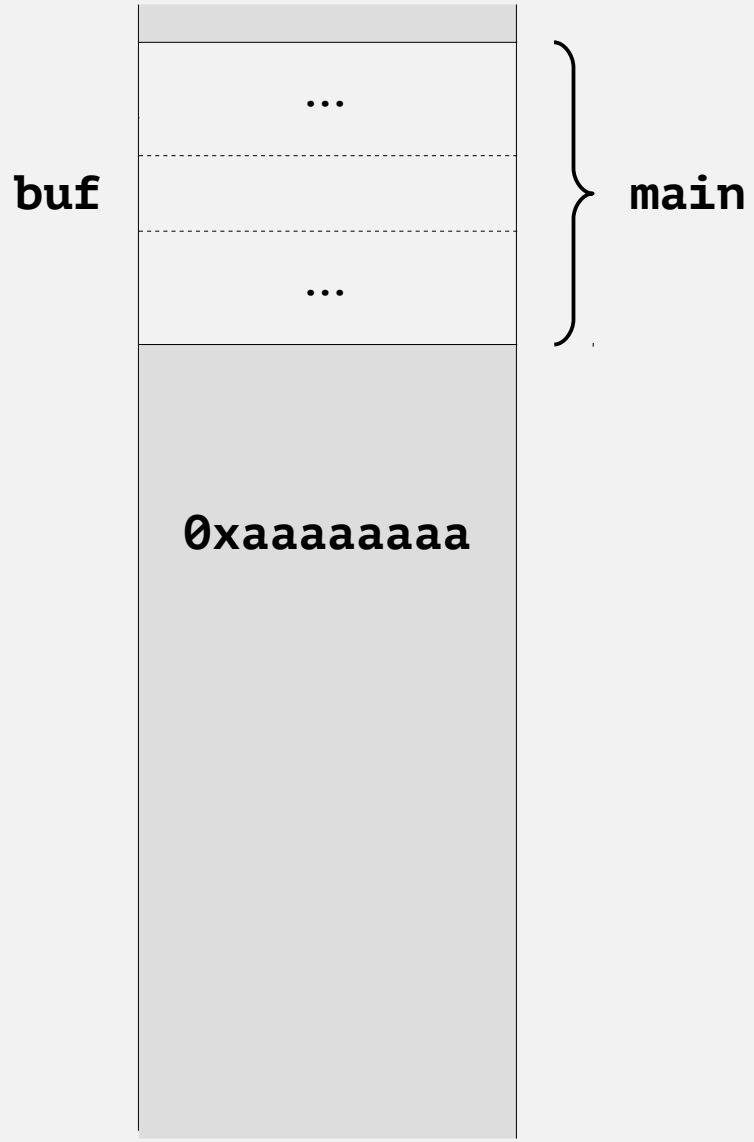

clang -ferase-stack=0xaa ...



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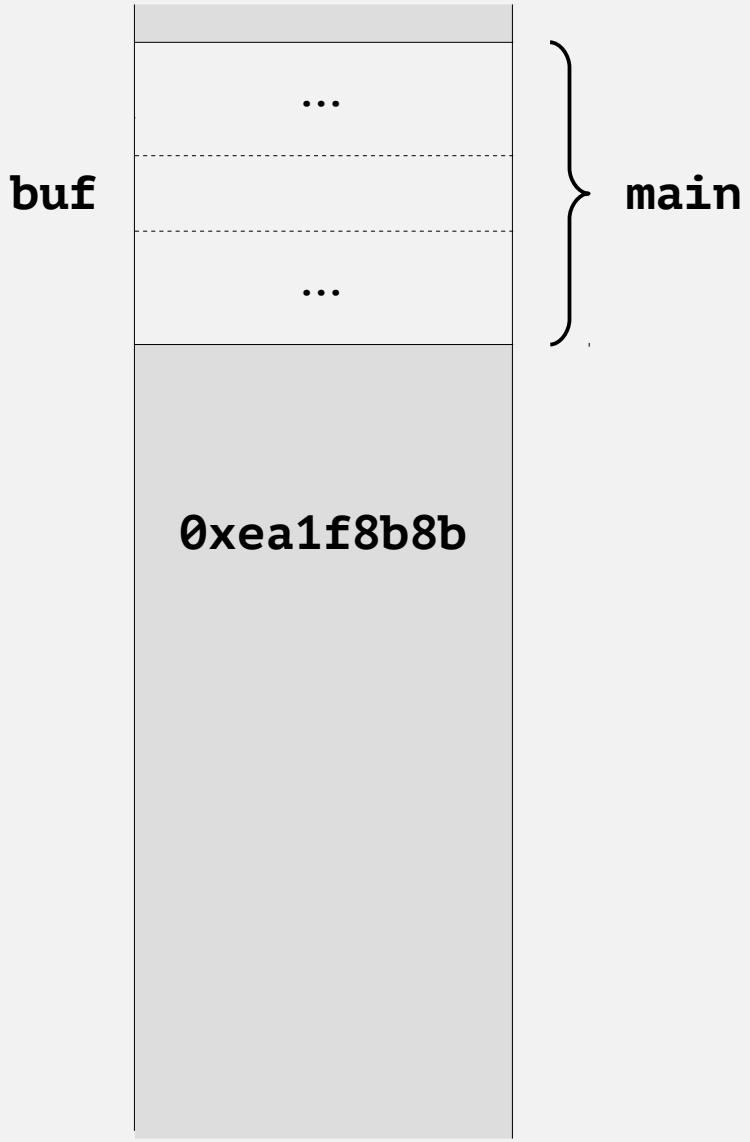
clang -frandomize-stack ...



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Summary of one Simple Problem

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- Clean up the stack for an individual function
  - `__attribute__ ((erase_stack))`

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  - `__attribute__ ((erase_stack))`
  - `__attribute__ ((erase_stack (`*n*`)))`

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  - `__attribute__ ((erase_stack))`
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- Always clean up the stack, including longjmp

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  - clang -ferase-stack …
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  - clang -ferase-stack …
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A Harder Problem

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A Harder Problem

```
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>

int globvar;

int main (int argc,
          char *argv[])
{
  uint32_t k, km;

  k = atoi (argv[1]);
  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

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A Harder Problem
Unoptimized Code

```c
#include <stdint.h>
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#include <stdlib.h>

int globvar;

int main (int argc,
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  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

```
...
        callq   atoi
        movl    %eax, -20(%rbp)
        movl    $1729, globvar
        movl    -20(%rbp), %eax
        imull   -20(%rbp), %eax
        xorl    %edx, %edx
        divl    globvar
        movl    %edx, -24(%rbp)
        cmpl    $1729, globvar
        je      .LBB0_2
        movabsq $.L.str, %rdi
        movb    $0, %al
        callq   printf
        movl    %eax, -28(%rbp)
.LBB0_2:
        movl    -24(%rbp), %eax
        addq    $32, %rsp
        popq    %rbp
        retq
```

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  uint32_t k, km;

  k = atoi (argv[1]);
  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

```
...
callq   strtol
movl    $1729, globvar(%rip)
imull   %eax, %eax
imulq   $792420225, %rax, %rcx
shrq    $32, %rcx
movl    %eax, %edx
subl    %ecx, %edx
shrl    %edx
addl    %ecx, %edx
shrl    $10, %edx
imull   $1729, %edx, %ecx
subl    %ecx, %eax
popq    %rcx
retq
```

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A Harder Problem
Optimized Code Fixed - Sort Of

```
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>

volatile int globvar;

int main (int argc,
          char *argv[])
{
  uint32_t k, km;

  k = atoi (argv[1]);
  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

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A Harder Problem
Optimized Code Fixed - Sort Of

```c
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>

volatile int globvar;

int main (int argc,
          char *argv[])
{
  uint32_t k, km;

  k = atoi (argv[1]);
  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

```
...
callq   strtol
movl    $1729, globvar(%rip)
imull   %eax, %eax
xorl    %edx, %edx
divl    globvar(%rip)
movl    %edx, %ebx
movl    globvar(%rip), %eax
cmpl    $1729, %eax
je      .LBB0_2
movl    $.Lstr, %edi
callq   puts
.LBB0_2:
movl    %ebx, %eax
popq    %rbx
retq
```

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A Harder Problem
Optimized Code Fixed - Sort Of

```c
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>

volatile int globvar;

int main (int argc,
          char *argv[])
{
  uint32_t k, km;

  k = atoi (argv[1]);
  globvar = 1729;
  km = (k * k) % globvar;

  if (globvar != 1729)
    printf ("Globvar wrong\n");

  return km;
}
```

```
...
callq   strtol
movl    $1729, globvar(%rip)
imull   %eax, %eax
xorl    %edx, %edx
divl    globvar(%rip)
movl    %edx, %ebx
movl    globvar(%rip), %eax
cmpl    $1729, %eax
je      .LBB0_2
movl    $.Lstr, %edi
callq   puts
.LBB0_2:
movl    %ebx, %eax
popq    %rbx
retq
```

How do we disable optimization for just one block?

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Leakage Aware Design Automation
The LADA Project

Prof Elisabeth Oswald
University of Bristol

Dr Dan Page
University of Bristol

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Leakage Aware Design Automation
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- EPSRC funded 4 year academic research project
  - supported by a team of RAs and PhD students

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- EPSRC funded 4 year academic research project
  - supported by a team of RAs and PhD students
- Embecosm is the "industrial supporter"
  - providing summer PhD internships
  - writing open source implementations for GCC & LLVM

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What is Information Leakage

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What is Information Leakage

"Information leakage happens whenever a system that is designed to be closed to an eavesdropper reveals some information to unauthorized parties nonetheless."

Wikipedia

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What is Information Leakage

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Differential Power Analysis

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Differential Power Analysis

```
int func (uint32_t  k)
{
  int  i, res = 0;

  for (i = 0; i < 10000000; i++)
    if (1 == (k & 1))
      res += k - 1;
    else
      {
        double r;
        r = sqrt ((double) k);
        res += (int) r;
      }
  return res;
}

int main (int argc,
          char *argv[])
{
  return func (atoi (argv[1]));
}
```

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Differential Power Analysis

```
int func (uint32_t  k)
{
  int  i, res = 0;

  for (i = 0; i < 10000000; i++)
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    else
      {
        double r;
        r = sqrt ((double) k);
        res += (int) r;
      }
  return res;
}

int main (int argc,
          char *argv[])
{
  return func (atoi (argv[1]));
}
```

```
$ time ./dpa 7

real    0m0.025s
user    0m0.024s
sys     0m0.000s
```

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Differential Power Analysis

```
int func (uint32_t  k)
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  int  i, res = 0;

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        r = sqrt ((double) k);
        res += (int) r;
      }
  return res;
}

int main (int argc,
          char *argv[])
{
  return func (atoi (argv[1]));
}
```

```
$ time ./dpa 7

real    0m0.025s
user    0m0.024s
sys     0m0.000s

$ time ./dpa 6

real    0m0.086s
user    0m0.084s
sys     0m0.000s
```

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Differential Power Analysis

```
int func (uint32_t  k)
{
  int  i, res = 0;

  for (i = 0; i < 10000000; i++)
    if (1 == (k & 1))
      res += k - 1;
    else
      {
        double r;
        r = sqrt ((double) k);
        res += (int) r;
      }
  return res;
}

int main (int argc,
          char *argv[])
{
  return func (atoi (argv[1]));
}
```

```
$ time ./dpa 7

real    0m0.025s
user    0m0.024s
sys     0m0.000s

$ time ./dpa 6

real    0m0.086s
user    0m0.084s
sys     0m0.000s
```

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Differential Power Analysis

```
int func (uint32_t  k)
{
  int  i, res = 0;

  for (i = 0; i < 10000000; i++)
    if (1 == (k & 1))
      res += k - 1;
    else
      {
        double r;
        r = sqrt ((double) k);
        res += (int) r;
      }
  return res;
}

int main (int argc,
          char *argv[])
{
  return func (atoi (argv[1]));
}
```

```
$ time ./dpa 7

real    0m0.025s
user    0m0.024s
sys     0m0.000s

$ time ./dpa 6

real    0m0.086s
user    0m0.084s
sys     0m0.000s
```

We need to worry about
- data dependent control flow
- data dependent instruction timing
- data dependent memory access

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Warning about Critical Variables Simple Cases (1)

```
int func (uint32_t  k)

{
  int  i, res = 0;

  if (1 == (k & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

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Warning about Critical Variables Simple Cases (1)

```
int func (uint32_t  k
  __attribute__ ((critvar)))
{
  int  i, res = 0;

  if (1 == (k & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

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    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv.c
gv.c:6:12: warning: critical
variable controlling flow 'k' [-
Wcritical-variable]
  if (1 == (k & 1))
            ^
```

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Warning about Critical Variables Simple Cases (2)

myinc.h:

```
extern uint32_t k
  __attribute__ ((critvar));
```

gv.c:

```
#include "myinc.h"
int func ()
{
  int  i, res = 0;


  if (1 == (k & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

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Warning about Critical Variables Simple Cases (2)

myinc.h:

```
extern uint32_t k
  __attribute__ ((critvar));
```

gv.c:

```
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{
  int  i, res = 0;


  if (1 == (k & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv.c
gv.c:6:12: warning: critical
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myinc.h:

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```
#include "myinc.h"
int func ()
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  if (1 == (k & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv.c
gv.c:6:12: warning: critical
variable controlling flow 'k' [-
Wcritical-variable]
  if (1 == (k & 1))
            ^
```

Critical variable usage is obvious

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Warning about Critical Variables
Not Quite So Simple Case

```
int func (uint32_t  k
  __attribute__ ((critvar)))
{
  int  i, res = 0;
  uint8_t b = k & 0xff;

  if (1 == (b & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

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Warning about Critical Variables
Not Quite So Simple Case

```
int func (uint32_t  k
  __attribute__ ((critvar)))
{
  int  i, res = 0;
  uint8_t b = k & 0xff;

  if (1 == (b & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv.c
gv.c:6:12: warning: critical
variable controlling flow 'b' [-
Wcritical-variable]
  if (1 == (b & 1))
            ^
```

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Warning about Critical Variables
Not Quite So Simple Case

```
int func (uint32_t  k
  __attribute__ ((critvar)))
{
  int  i, res = 0;
  uint8_t b = k & 0xff;

  if (1 == (b & 1))
    res += k - 1;
  else
    {
      double r;
      r = sqrt ((double) k);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv.c
gv.c:6:12: warning: critical
variable controlling flow 'b' [-
Wcritical-variable]
  if (1 == (b & 1))
            ^
```

Critical variable usage needs to understand local data flow

- can we always get this right?

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Warning about Critical Variables Harder Case

```
gv1.c:
int func1 (uint32_t  k
  __attribute__ ((critvar)))
{
  return func2 (k);
}

gv2.c:
int func2 (uint32_t  x)
{
  int  i, res = 0;

  if (1 == (x & 1))
    res += x - 1;
  else
    {
      double r;
      r = sqrt ((double) x);
      res += (int) r;
    }
  return res;
}
```

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Warning about Critical Variables Harder Case

gv1.c:

```
int func1 (uint32_t  k
  __attribute__ ((critvar)))
{
  return func2 (k);
}
```

gv2.c:

```
int func2 (uint32_t  x)
{
  int  i, res = 0;

  if (1 == (x & 1))
    res += x - 1;
  else
    {
      double r;
      r = sqrt ((double) x);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv1.c
$ clang -c gv2.c
$ clang gv1.o gv2.o
$
```

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Warning about Critical Variables Harder Case

```
gv1.c:
int func1 (uint32_t  k
  __attribute__ ((critvar)))
{
  return func2 (k);
}

gv2.c:
int func2 (uint32_t  x)
{
  int  i, res = 0;

  if (1 == (x & 1))
    res += x - 1;
  else
    {
      double r;
      r = sqrt ((double) x);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -c gv1.c
$ clang -c gv2.c
$ clang gv1.o gv2.o
$
```

No warning! Individually neither function can see a critical variable is controlling flow.

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Warning about Critical Variables Harder Case

```
gv1.c:
int func1 (uint32_t  k
  __attribute__ ((critvar)))
{
  return func2 (k);
}

gv2.c:
int func2 (uint32_t  x)
{
  int  i, res = 0;

  if (1 == (x & 1))
    res += x - 1;
  else
    {
      double r;
      r = sqrt ((double) x);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -flto -c gv1.c
$ clang -flto -c gv2.c
$ clang -flto gv1.o gv2.o
gv2.c:5:12: warning: critical
variable controlling flow 'x' [-
Wcritical-variable]
  if (1 == (x & 1))
            ^
```

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Warning about Critical Variables Harder Case

```
gv1.c:
int func1 (uint32_t  k
  __attribute__ ((critvar)))
{
  return func2 (k);
}

gv2.c:
int func2 (uint32_t  x)
{
  int  i, res = 0;

  if (1 == (x & 1))
    res += x - 1;
  else
    {
      double r;
      r = sqrt ((double) x);
      res += (int) r;
    }
  return res;
}
```

```
$ clang -flto -c gv1.c
$ clang -flto -c gv2.c
$ clang -flto gv1.o gv2.o
gv2.c:5:12: warning: critical
variable controlling flow 'x' [-
Wcritical-variable]
  if (1 == (x & 1))
            ^
```

Critical variable usage needs to understand *global* data flow

- can we always get this right?

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Warning about Critical Variables Summary

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Warning about Critical Variables Summary

- Simple cases are easy

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Warning about Critical Variables Summary

- Simple cases are easy
- Most cases need dataflow analysis
  - LTO for programs of any size

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Warning about Critical Variables Summary

- Simple cases are easy
- Most cases need dataflow analysis
  - LTO for programs of any size
- What if we get it wrong
  - false positives mean lots of fruitless debugging
  - false negatives mean “bad” code gets through

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Warning about Critical Variables Summary

- Simple cases are easy
- Most cases need dataflow analysis
  - LTO for programs of any size
- What if we get it wrong
  - false positives mean lots of fruitless debugging
  - false negatives mean “bad” code gets through
- It is not just control flow that leaks
  - what about variation in memory access?
  - what about variation in instruction timing?
  - what about energy?

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8-Bit Processor Multiply Instruction Heat Map

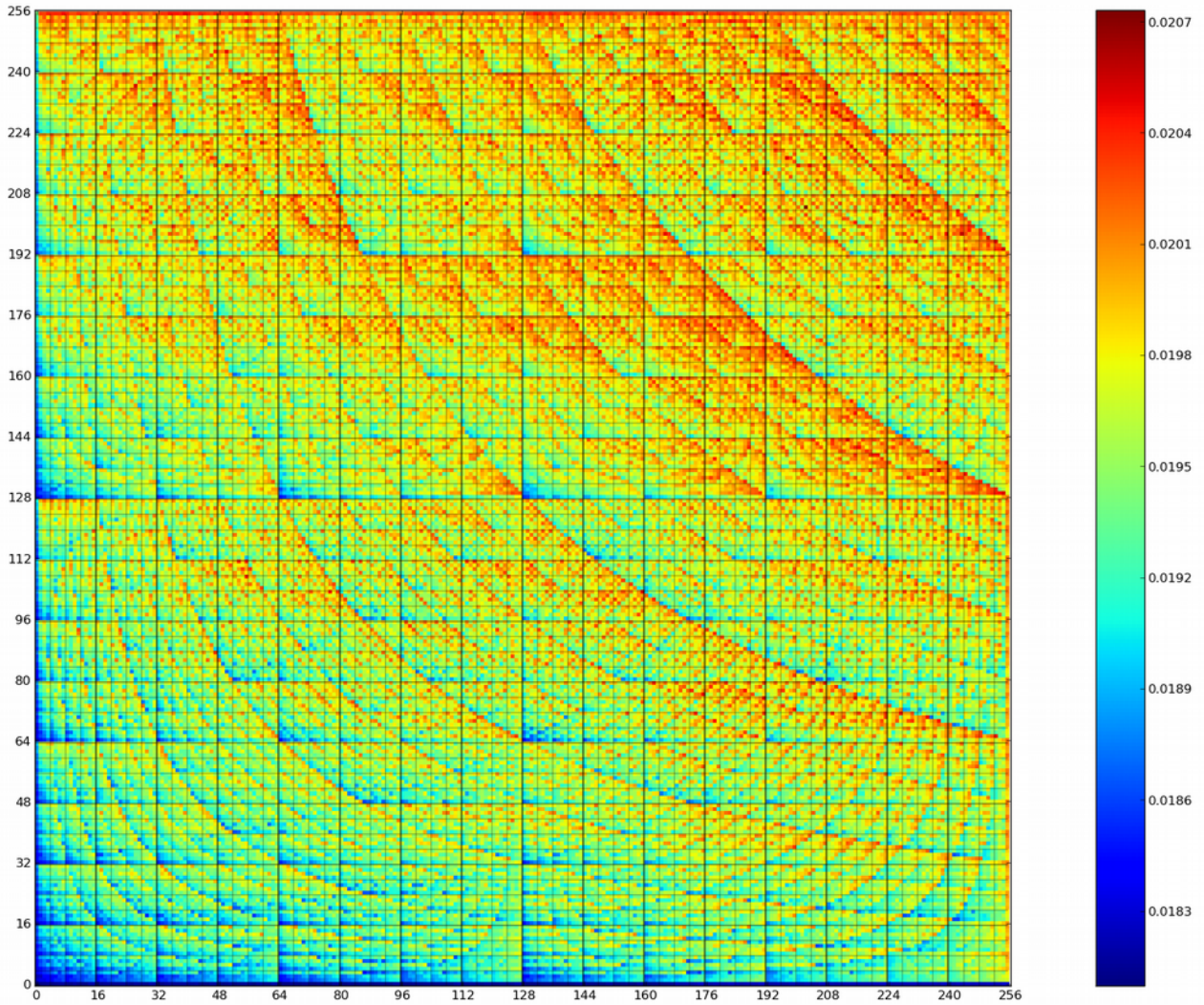

Image: Dr James Pallister, University of Bristol

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Bit Splitting By Hand

```
#include <stdint.h>

uint8_t k0, k1, k2, k3;

void inc_key32 ()
{
  k3++;
  if (0 == k3)
    {
      k2++;
      if (0 == k2)
        {
          k1++;
          if (0 == k1)
            k0++;
        }
    }
}
```

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Bit Splitting By Hand

```
#include <stdint.h>

uint8_t k0, k1, k2, k3;

void inc_key32 ()
{
  k3++;
  if (0 == k3)
    {
      k2++;
      if (0 == k2)
        {
          k1++;
          if (0 == k1)
            k0++;
        }
    }
}
```

- Spread key through memory
  - can't be scanned for

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Bit Splitting By Hand

```
#include <stdint.h>

uint8_t k0, k1, k2, k3;

void inc_key32 ()
{
  k3++;
  if (0 == k3)
    {
      k2++;
      if (0 == k2)
        {
          k1++;
          if (0 == k1)
            k0++;
        }
    }
}
```

- Spread key through memory
  - can't be scanned for
- This *ought* to work

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Bit Splitting By Hand

```
#include <stdint.h>

uint8_t k0, k1, k2, k3;

void inc_key32 ()
{
  k3++;
  if (0 == k3)
    {
      k2++;
      if (0 == k2)
        {
          k1++;
          if (0 == k1)
            k0++;
        }
    }
}
```

- Spread key through memory
  - can't be scanned for
- This *ought* to work
- But it is hard work
  - just byte splitting here!

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Bit Splitting By Hand

```
#include <stdint.h>

uint8_t k0, k1, k2, k3;

void inc_key32 ()
{
  k3++;
  if (0 == k3)
    {
      k2++;
      if (0 == k2)
        {
          k1++;
          if (0 == k1)
            k0++;
        }
    }
}
```

- Spread key through memory
  - can't be scanned for
- This *ought* to work
- But it is hard work
  - just byte splitting here!
- Optimization
  - might combine k0,k1,k2,k3
  - benefits wiped out

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Bit Splitting Automated

```
#include <stdint.h>

uint32_t k
  __attribute__ ((bitsplit));

void inc_key32 ()
{
  k++;
}
```

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Bit Splitting Automated

```
#include <stdint.h>

uint32_t k
  __attribute__ ((bitsplit));

void inc_key32 ()
{
  k++;
}
```

- Trivial for the programmer

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Bit Splitting Automated

```
#include <stdint.h>

uint32_t k
  __attribute__ ((bitsplit));

void inc_key32 ()
{
  k++;
}
```

- Trivial for the programmer
- Compiler can ensure operations are optimal

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Bit Splitting Automated

```
#include <stdint.h>

uint32_t k
  __attribute__ ((bitsplit));

void inc_key32 ()
{
  k++;
}
```

- Trivial for the programmer
- Compiler can ensure operations are optimal
- Compiler will never optimize

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Bit Splitting Automated

```
#include <stdint.h>

uint32_t k
  __attribute__ ((bitsplit));

void inc_key32 ()
{
  k++;
}
```

- Trivial for the programmer
- Compiler can ensure operations are optimal
- Compiler will never optimize
- Same dataflow issues as critical variables

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Other Areas To Investigate

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Other Areas To Investigate

- Atomicity – balancing control flow paths

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Other Areas To Investigate

- Atomicity – balancing control flow paths
- Superoptimizing for minimal leakage

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- Algorithmic choice

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Other Areas To Investigate

- Atomicity – balancing control flow paths
- Superoptimizing for minimal leakage
- Algorithmic choice
- Instruction Set Extensions for minimizing leakage

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Other Areas To Investigate

- Atomicity – balancing control flow paths
- Superoptimizing for minimal leakage
- Algorithmic choice
- Instruction Set Extensions for minimizing leakage
- Instruction shuffling

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Thank You

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