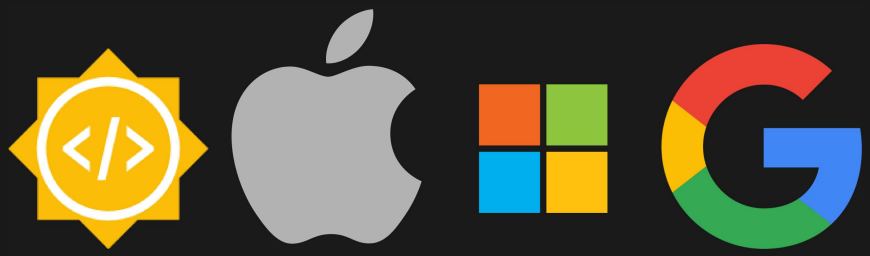
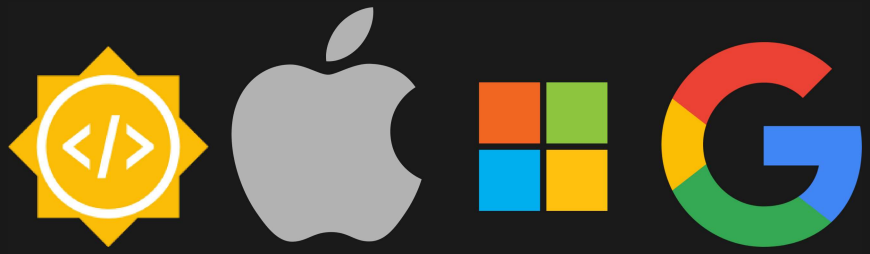
Algorithms from a Compiler Developer's Toolbox

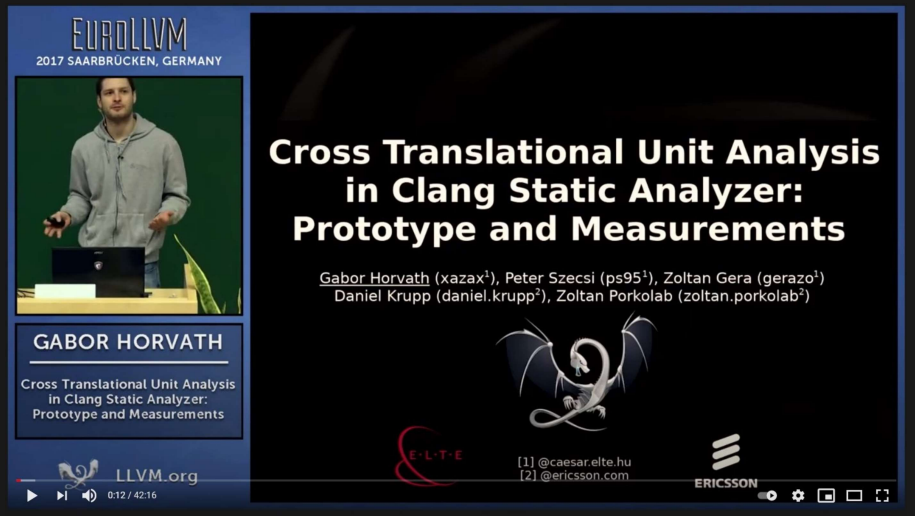
Gábor Horváth

ALGORITHMS FROM A COMPILER DEVELOPER'S TOOLBOX

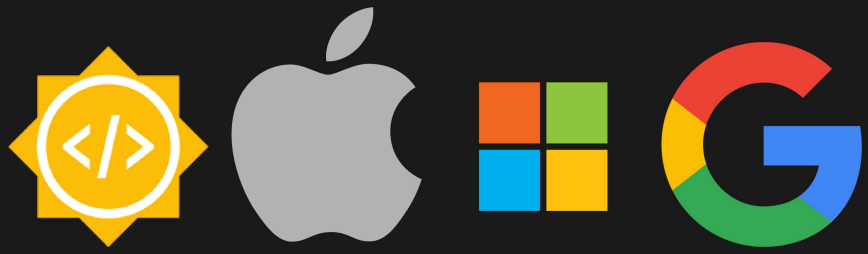
Gabor Horvath (He/Him)

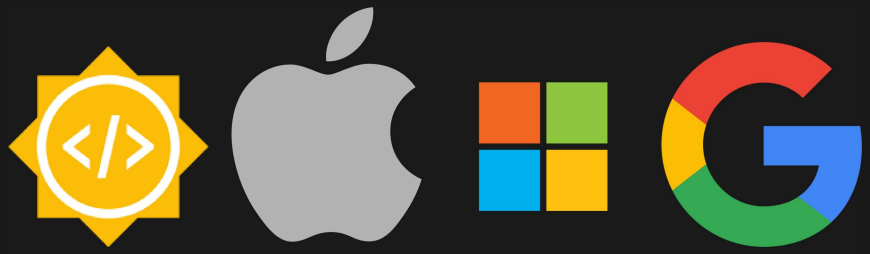


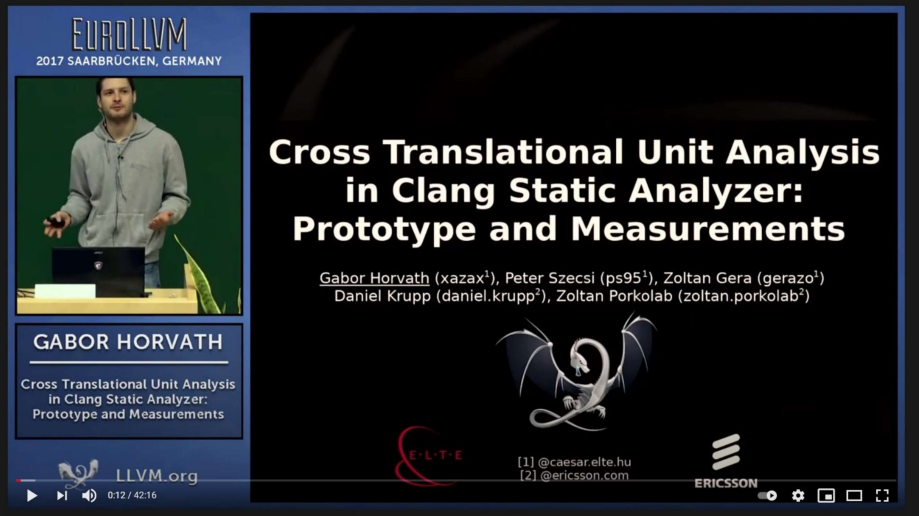




2017 EuroLLVM Developers' Meeting: G. Horvath "Cross Translational Unit Analysis in Clang ..."







2017 EuroLLVM Developers' Meeting: G. Horvath "Cross Translational Unit Analysis in Clang ..."

CppCon 2018: Herb Sutter "Thoughts on a more powerful and simpler C++ (5 of N)"

AGENDA

- Why study compilers?

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- Not just a constant factor!

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- The beautiful algebra in our loops

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- Counting values

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- Sources of ~~redundant~~ redundancy
- Counting values
- Where to find more

WHY STUDY COMPILERS?

They use beautiful algorithms and data structures

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- Graph algorithms

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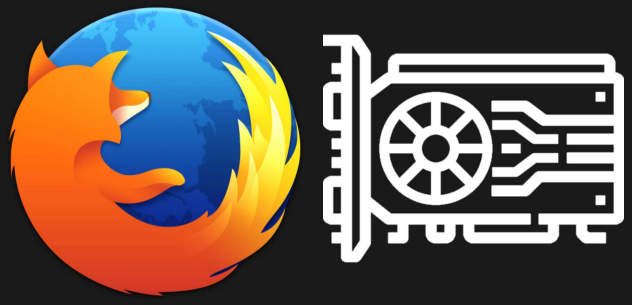

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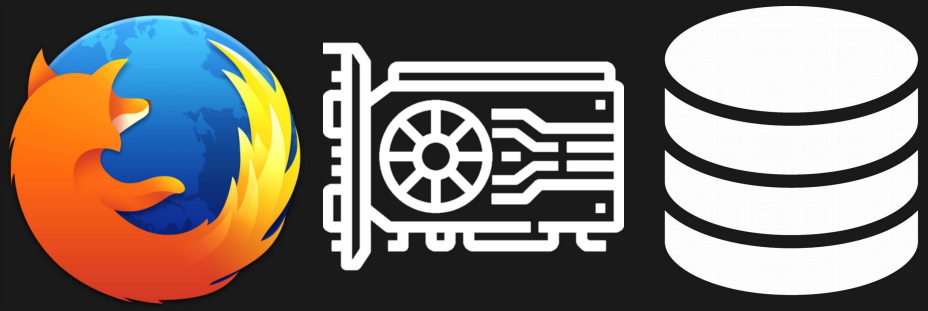

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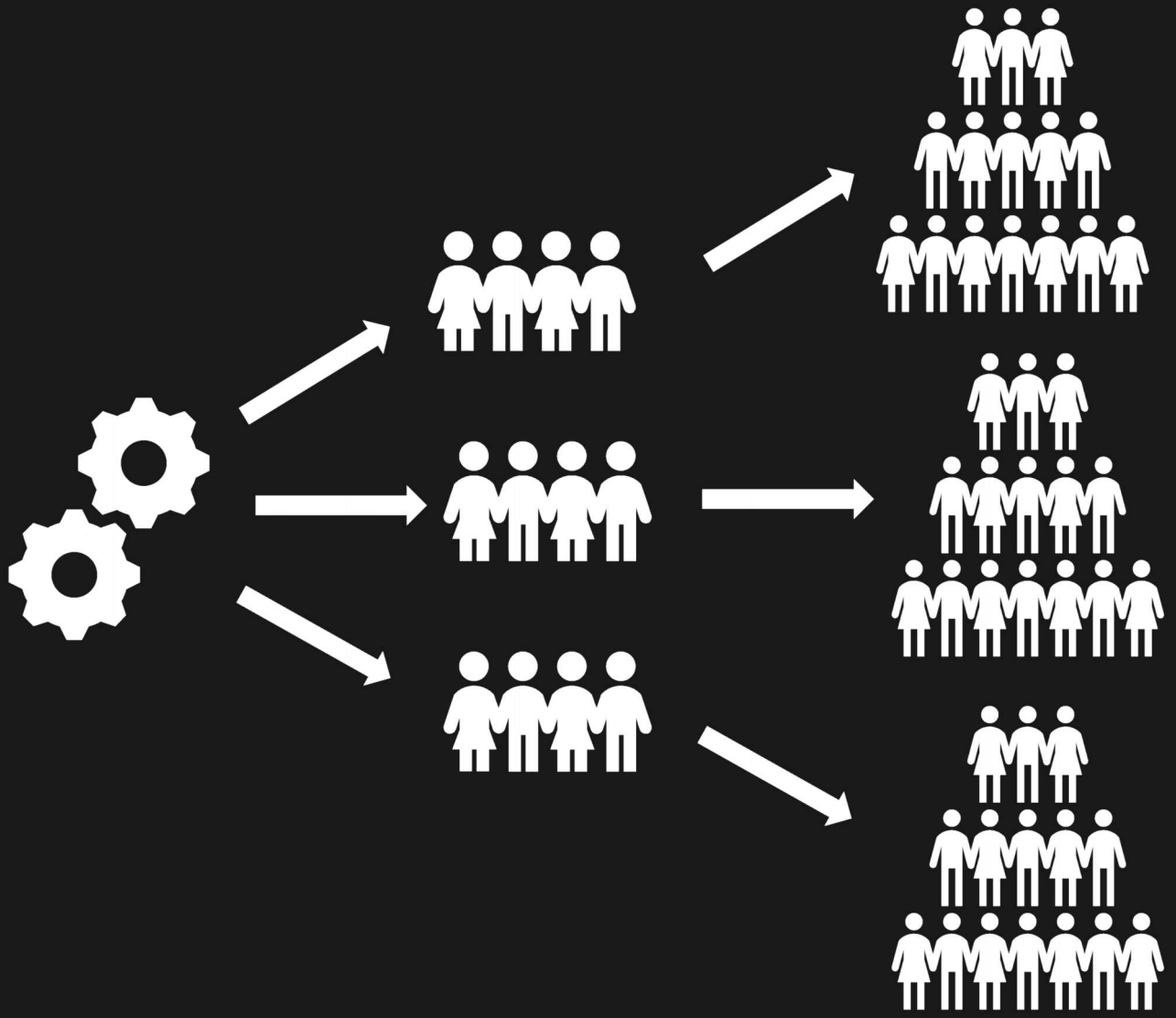
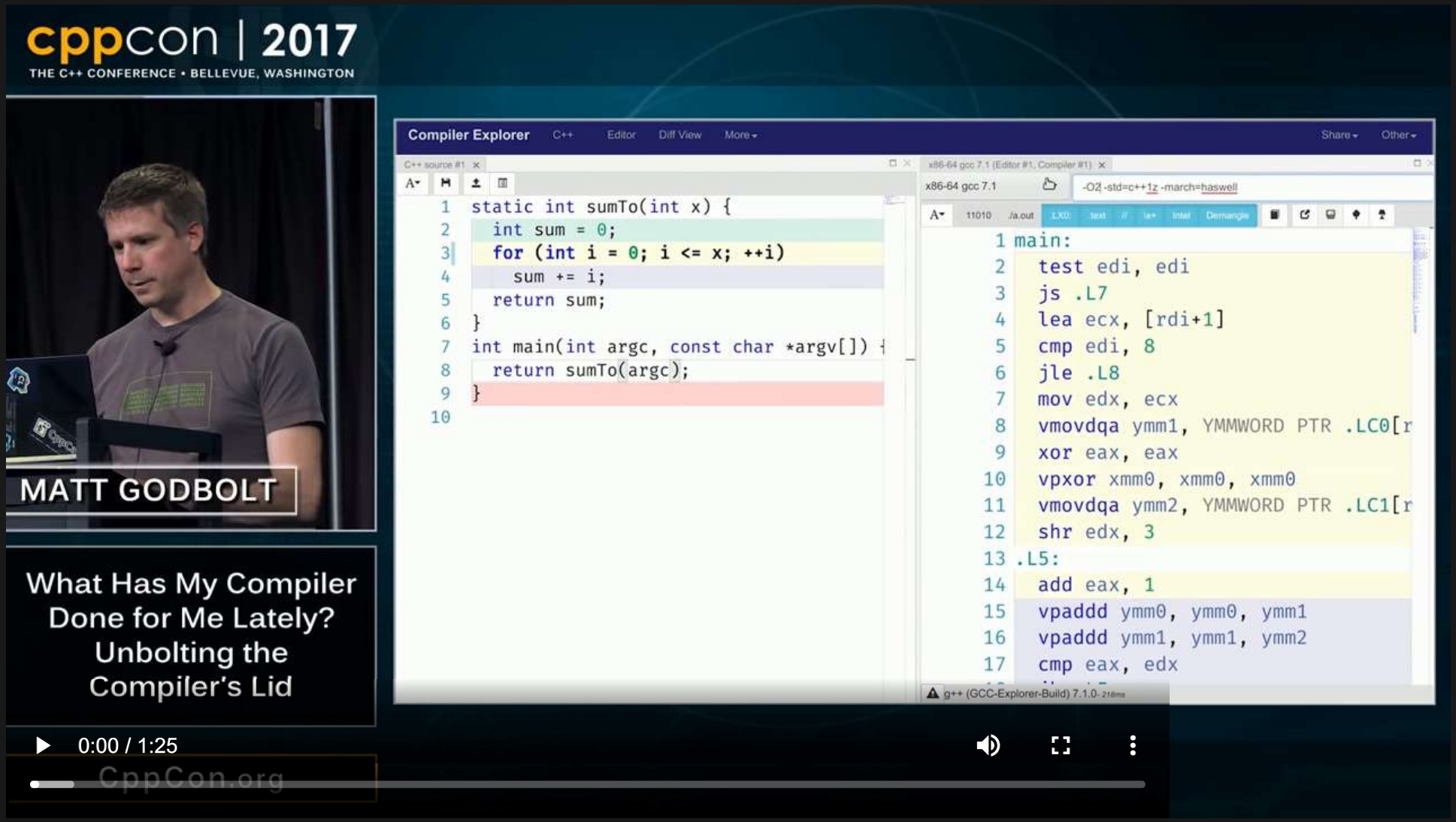


LOOP STRENGTH REDUCTION

CONSTANT FACTORS ONLY?



IS IT ROBUST?

LET'S UNBOLT THE COMPILER'S LID!

IT'S MATH

CHAINS OF RECURRENCES

RECURSIVE FUNCTIONS 101

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$$n! = \begin{cases} 1, \text{ for } n = 0 \\ n * (n-1)! \text{ otherwise} \end{cases}$$

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... BUT WHY?

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int v = initial;
for(int i = 0; i < max; ++i)
    v += increment;
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Iter. increment

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Iter.		increment
0	initial	

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Iter.	increment
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1	initial + increment
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3	initial + 3*increment

... MORE COMPLEX VALUES?

```
for(int i = 0; i < max; ++i)
    compute(i*i);
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0. 0
1. 1
2. 4
3. 9
4. 16

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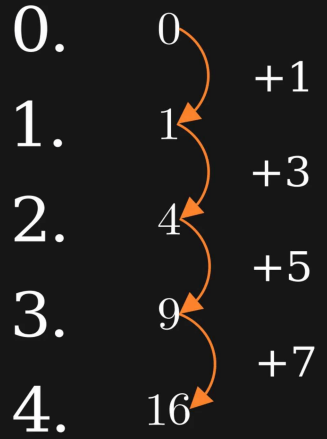

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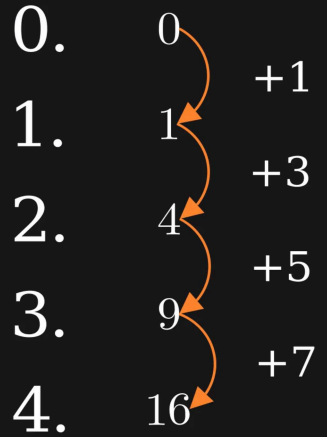

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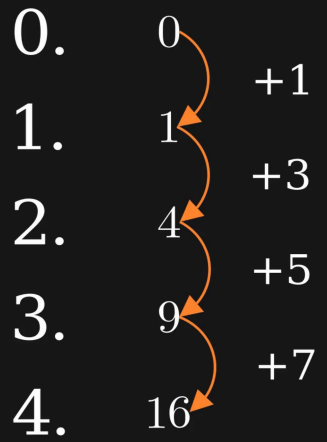

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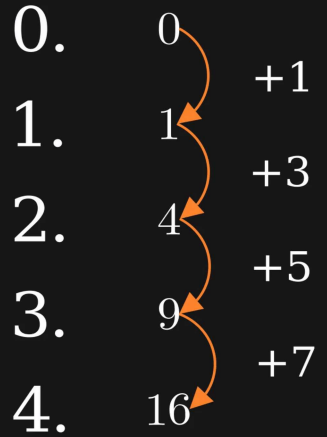

INTERLUDE: WHAT IS AN ALGEBRA?

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From Arabic al-jabr: reunion of broken parts.

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Study of symbols and the rules for manipulating symbols.

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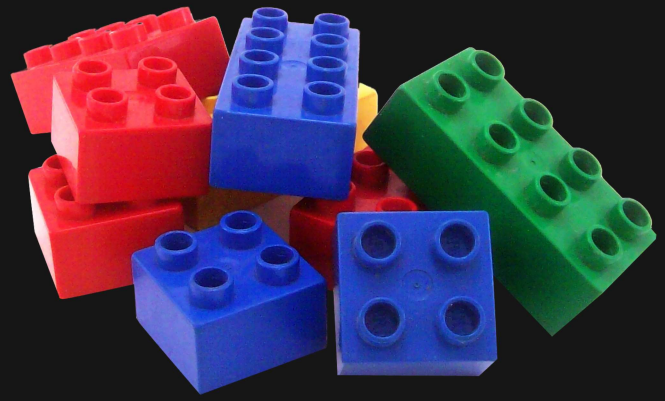

THE LEGO ALGEBRA

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- Closed

```
stack :: lego -> lego -> lego
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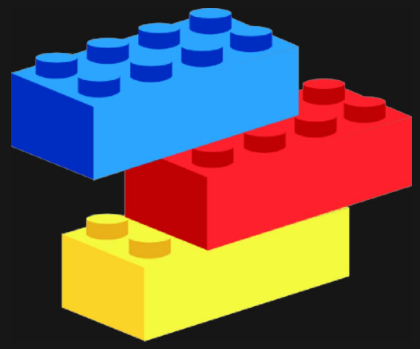

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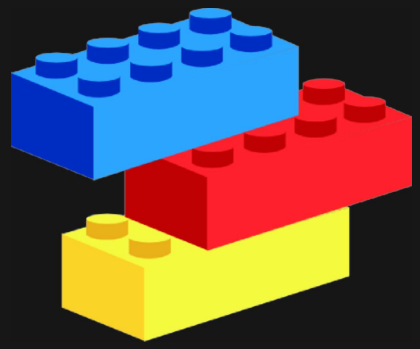

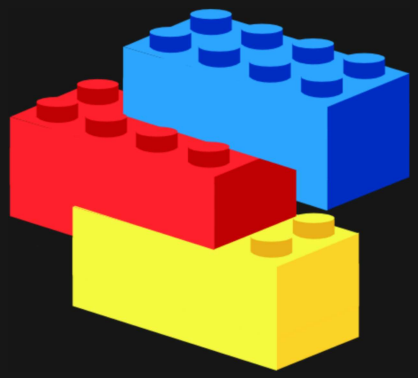

THE LEGO ALGEBRA

- Closed

  ```
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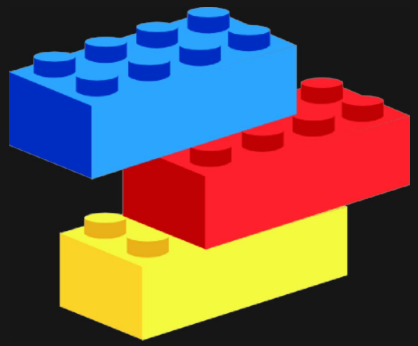
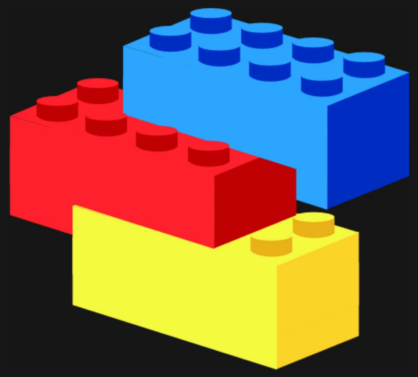
  ```

- Rules
- Identities

  ```
  stack Y (stack R B) == stack (stack Y R) B
  ```





OPERATIONS, IDENTITIES

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$$c + \{a, \ + \ , b\} =$$

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... MORE COMPLEX VALUES, REVISITED!

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$f_i(n)$

f_i

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for(i=0; i < m; ++i)
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$$f_i(n)$$

$$a \leftarrow 0 b \leftarrow 1 e \leftarrow 0 f \leftarrow 1$$

$$f_{i*i}(n) = \{0$$

$$\{a, +, b\} * \{e, +, f\} = \{a * e$$

$$\{0, +, 1\} * \{0, +, 1\} = \{0 * 0,$$

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$$a \leftarrow 0 b \leftarrow 1 e \leftarrow 0 f \leftarrow 1$$

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$$\{0, +, 1\} * \{0, +$$

THE POWER OF ALGEBRAS

```
for(i=0; i < m; ++i)
  v[i] = (i + 1)*(i + 1) - i*i - 2*i;
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$$f_{2i}(n) = ?$$

$$f_{i+1}(n) = ?$$

$$f_{(i+1)^2}(n) = ?$$

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$$f_{(i+1)^2}(n) = \{1, +, 3, +, 2\}$$

$$f_{(i+1)^2 - i^2}(n) = ?$$

$$f_{(i+1)^2-i^2-2i}(n) = ?$$

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$$f_{2^i}(n) = \{0, +, 2\}$$

$$f_{i+1}(n) = \{1, +, 1\}$$

$$f_{(i+1)^2}(n) = \{1, +, 3, +, 2\}$$

$$f_{(i+1)^2 - i^2}(n) = \{1, +, 2, +, 0\}$$

$$f_{(i+1)^2-i^2-2i}(n) = \{1, +, 0\}$$

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```
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```

$$(i+1)^2 = i^2 + 2i + 1$$

CLOSED FROMS

$$\{a, +, b\}$$

CLOSED FROMS

$$\{a, \ + \ , b\}$$

$$a, a + b, a + 2b, a + 3b, \ldots$$

CLOSED FROMS

$$\{a, \ + \ , b\}$$

$$a, a + b, a + 2b, a + 3b, \ldots$$

Arithmetic series with the difference of b!

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$$a, a + b, a + 2b, a + 3b, \ldots$$

Arithmetic series with the difference of b!

$$f(n) = \{c, \ +, a, \ +, b\}$$

CLOSED FROMS

$$\{a, \ + \ , b\}$$

$$a, a + b, a + 2b, a + 3b, \ldots$$

Arithmetic series with the difference of b!

$$f(n) = \{c, \ + \ , a, \ + \ , b\}$$

$$f(n) = c + \sum_{i=0}^{n} \{a, \ + \ , b\}$$

CLOSED FROMS

$$\{a, \ +, b\}$$

$$a, a + b, a + 2b, a + 3b, \ldots$$

Arithmetic series with the difference of b!

$$f(n) = \{c, \ +, a, \ +, b\}$$

$$f(n) = c + \frac{n[2a + b(n-1)]}{2}$$

CLOSED FROMS

$$\{a, \ +, b\}$$

$$a, a + b, a + 2b, a + 3b, \ldots$$

Arithmetic series with the difference of b!

$$f(n) = \{c, \ +, a, \ +, b\}$$

$$f(n) = c + \frac{n[2a + b(n-1)]}{2}$$

There are more...

STRENGTH REDUCTION REVISITED

```
void g(int);
void f() {
  for(int i = 0; i < 20; i += 1
  {
    g(5 * i);
  }
}
```

STRENGTH REDUCTION REVISITED

```
void g(int);
void f() {
  for(int i = 0; i < 20; i +=
  {
    g(5 * i);
  }
}
```

$$f_{5i}(n) = 5 * \{0, +, 1\} = \{0, +$$

STRENGTH REDUCTION REVISITED

```
void g(int);
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  }
}
```

$$f_{5i}(n) = 5 * \{0, +, 1\} = \{0, +$$

We have the strength reduc
format for free.

STRENGTH REDUCTION REVISITED

```
void g(int);
void f() {
  for(int i = 0; i < 100; i +=
  {
    g(i);
  }
}
```

$$f_{5i}(n) = 5 * \{0, +, 1\} = \{0, +$$

We have the strength reduc
format for free.

STRENGTH REDUCTION REVISITED

```
void g(int *);
void f() {
  int t[20];
  for(int i = 0; i < 20; i += 1
  {
    t[i] = (i + 1) * (i + 1) +
                3*i - 5;
  }
  g(t);
}
```

STRENGTH REDUCTION REVISITED

```
void g(int *);
void f() {
  int t[20];
  for(int i = 0; i < 20; i +=
  {
    t[i] = (i + 1) * (i + 1)
                3*i - 5;
  }
  g(t);
}
```

Initially: 4 additions, 2 multiplications

STRENGTH REDUCTION REVISITED

```
void g(int *);
void f() {
  int t[20];
  for(int i = 0; i < 20; i +=
  {
    t[i] = (i + 1) * (i + 1)
                3*i - 5;
  }
  g(t);
}
```

Initially: 4 additions, 2 multiplications

$$f_{(i+1)^2+3i-5}(n) = \{-4, +, 6,$$

STRENGTH REDUCTION REVISITED

```
void g(int *);
void f() {
  int t[20];
  a = -4;
  b = 6;
  for(int i = 0; i < 20; i +=
  {
    t[i] = a;
    a += b;
    b += 2;
  }
  g(t);
}
```

Initially: 4 additions, 2 multiplications

$$f_{(i+1)^2+3i-5}(n) = \{-4, +, 6,$$

After: 2 additions

CLOSED FORM SUM REVISITED

$$f_{result}(n) = \{0, +, 0, +, 1\}$$

LLVM SCEV DEMO

WHERE TO LEARN MORE?

GCC

Academic papers

`llvm::ScalarEvolution`

RECAPPING CHAINS OF RECURRENCES

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- Great to model some loop variant values

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- Closed forms

RECAPPING CHAINS OF RECURRENCES

- Great to model some loop variant values
- Algebra of simple recursive functions
- Algebraic simplifications
- Strength reduction
- Closed forms
- Many more...

VALUE NUMBERING

SOURCES OF REDUNDANCY

```
1 int calculate(int a, int b) {
2         int result = a * b + 2;
3         if (a % 2 == 0) {
4                 result += a * b;
5         }
6         return result;
7 }
```

SOURCES OF REDUNDANCY

```
1 int calculate(int a, int b) {
2         int tmp = a * b;
3         int result = tmp + 2;
4         if (a % 2 == 0) {
5                 result += tmp;
6         }
7         return result;
8 }
```

SOURCES OF REDUNDANCY

```
1 int foo() {
2     int matrix[5][5] = {...};
3
4     matrix[1][2] = bar();
5     matrix[1][3] = baz();
6
7     calculate(matrix);
8 }
```

SOURCES OF REDUNDANCY

```
1 int foo() {
2     int matrix[5][5] = {...};
3
4     matrix[1][2] = bar();
5     matrix[1][3] = baz();
6
7     calculate(matrix);
8 }
```

```
*((int*)matrix + ROW * sizeof(int) * 1 + sizeof(int) * 2) = ba
*((int*)matrix + ROW * sizeof(int) * 1 + sizeof(int) * 3) = ba
```

SOURCES OF REDUNDANCY

```c
int dead_code() {
    int a;
    a = 5; // dead
    a = 7;
    return a;
}

int copy_propagation() {
    int x = get_value();
    int y = x;
    int z = y;
    return z;
}
```

SOURCES OF REDUNDANCY

```c
int dead_code() {
    int a;
    a = 7;
    return a;
}

int copy_propagation() {
    int x = get_value();
    return x;
}
```

PASSES OF A COMPILER

BRIL

https://github.com/sampsyo/bril

Bril (the Big Red Intermediate Language) is a compiler IR made for teaching CS 6120, a grad compilers course. It is an extremely simple instruction-based IR that is meant to be extended. Its canonical representation is JSON, which makes it easy to build tools from scratch to manipulate it.

BRIL EXAMPLE

BRIL EXAMPLE

```
> cat add.bril
@main {
  v0: int = const 1;
  v1: int = const 2;
  v2: int = add v0 v1;
  print v2;
}
```

BRIL EXAMPLE

```
> cat add.bril | bril2json
{
  "functions": [
    {
      "instrs": [
        {
          "dest": "v0",
          "op": "const",
          "type": "int",
          "value": 1
        },
        {
          "dest": "v1",
          "op": "const",
          "type": "int",
          "value": 2
        },
        {
          "args": [
            "v0",
            "v1"
          ],
          "dest": "v2",
          "op": "add",
          "type": "int"
        },
        {
          "args": [
            "v2"
          ],
          "op": "print"
        }
      ],
      "name": "main"
    }
  ]
}
```

BRIL EXAMPLE

```
> cat add.bril | bril2json | brili
3
```

BRIL EXAMPLE

```
> cat negate_add.py
import json
import sys

ir = json.load(sys.stdin)

for func in ir["functions"]:
    for instr in func["instrs"]:
        if instr["op"] == "add":
            instr["op"] = "sub"

print(json.dumps(ir, indent=4))
```

BRIL EXAMPLE

```
> cat add.bril | bril2json | python3 negate_add.py | bril2txt
@main {
  v0: int = const 1;
  v1: int = const 2;
  v2: int = sub v0 v1;
  print v2;
}
```

BRIL EXAMPLE

```
> cat add.bril | bril2json | python3 negate_add.py | brili
-1
```

BRIL EXAMPLE

```
> cat add.bril | bril2json | python3 negate_add.py | python3 negate_add.py | python3 negate_add.py | brili
-1
```

BRIL RECAP

BRIL RECAP

- No compilation, fast experimenting

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- Small core language, trivial API

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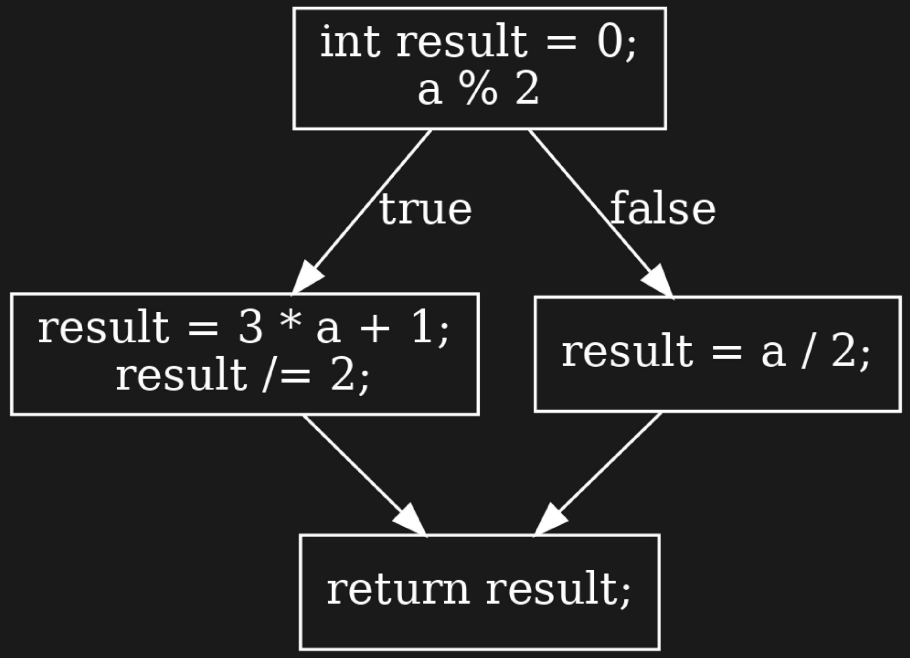
BRIL RECAP

- No compilation, fast experimenting
- Small core language, trivial API
- Easily composable pipeline
- Tooling included

OPTIMIZATION TERMINOLOGY 101

```
int collatz(int a) {
  int result = 0;
  if (a % 2) {
    result = 3 * a + 1;
    result /= 2;
  } else {
    result = a/2;
  }
  return result;
}
```



OPTIMIZATION TERMINOLOGY 101

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  } else {
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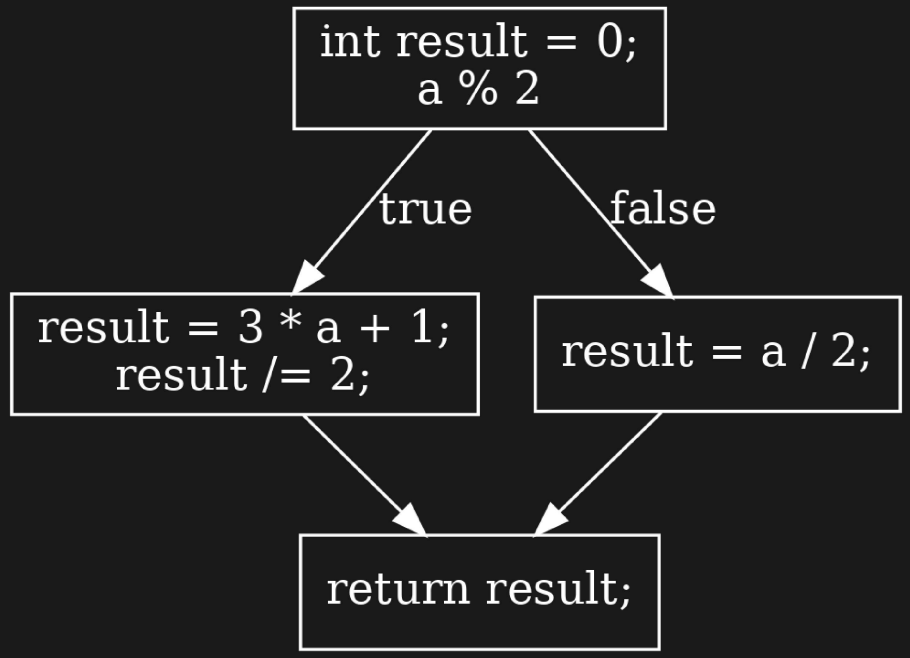
  }
  return result;
}
```



- CFG, Basic Block

OPTIMIZATION TERMINOLOGY 101

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    result /= 2;
  } else {
    result = a/2;
  }
  return result;
}
```

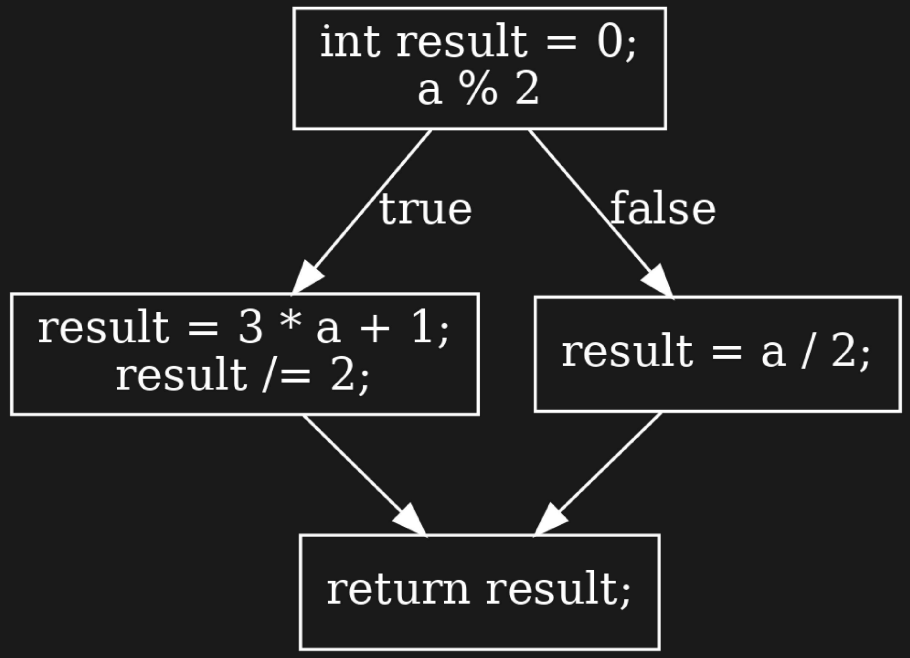

- CFG, Basic Block
- Local, super-local (loops, EBBs), global

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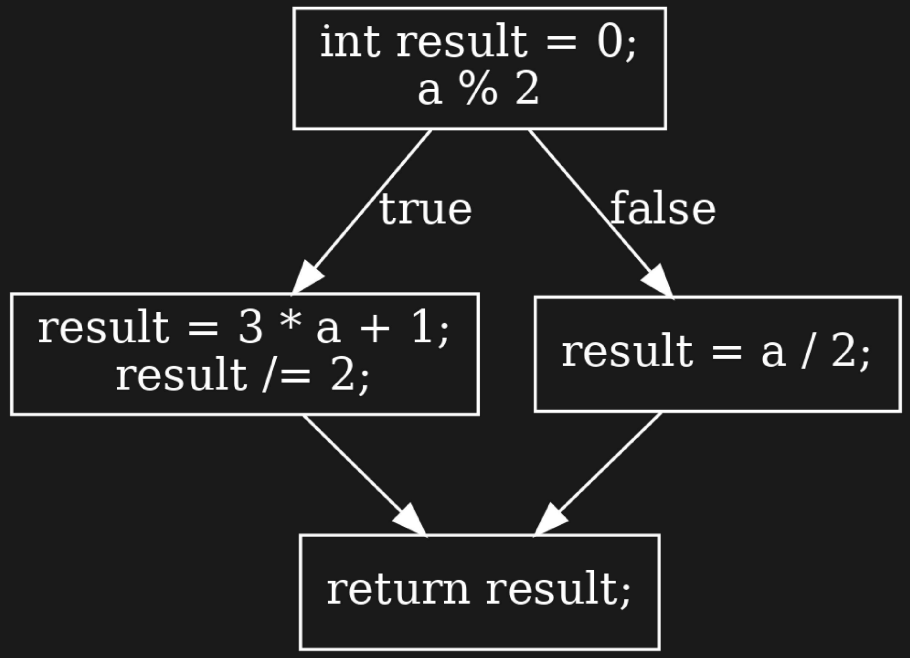


- CFG, Basic Block
- Local, super-local (loops, EBBs), global
- Intra-, inter-procedural

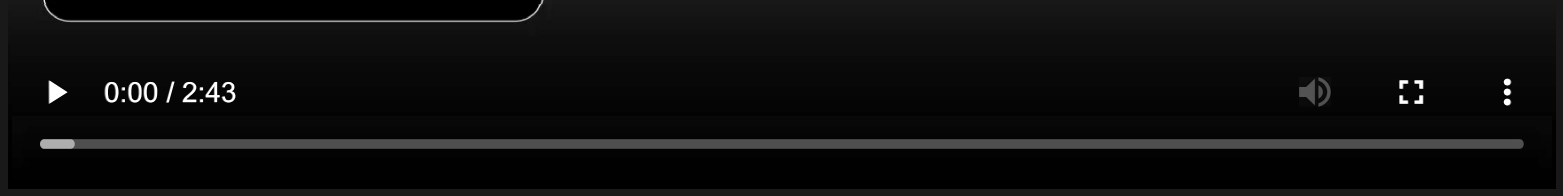
LOCAL VALUE NUMBERING

- Reasons about values, not variables
- Helps eliminating dead code
- Does common subexpression elimination
- Does copy propagation
- And more...

THE LVN ALGORITHM

Env # Val Home

```
int f(int v) {
  int a = 5;
  a = v;
  int x = 3;
  int y = x;
  int b = y;
  int s = a + b;
  int q = b + a;
  int p = s * q;
  return p;
}
```



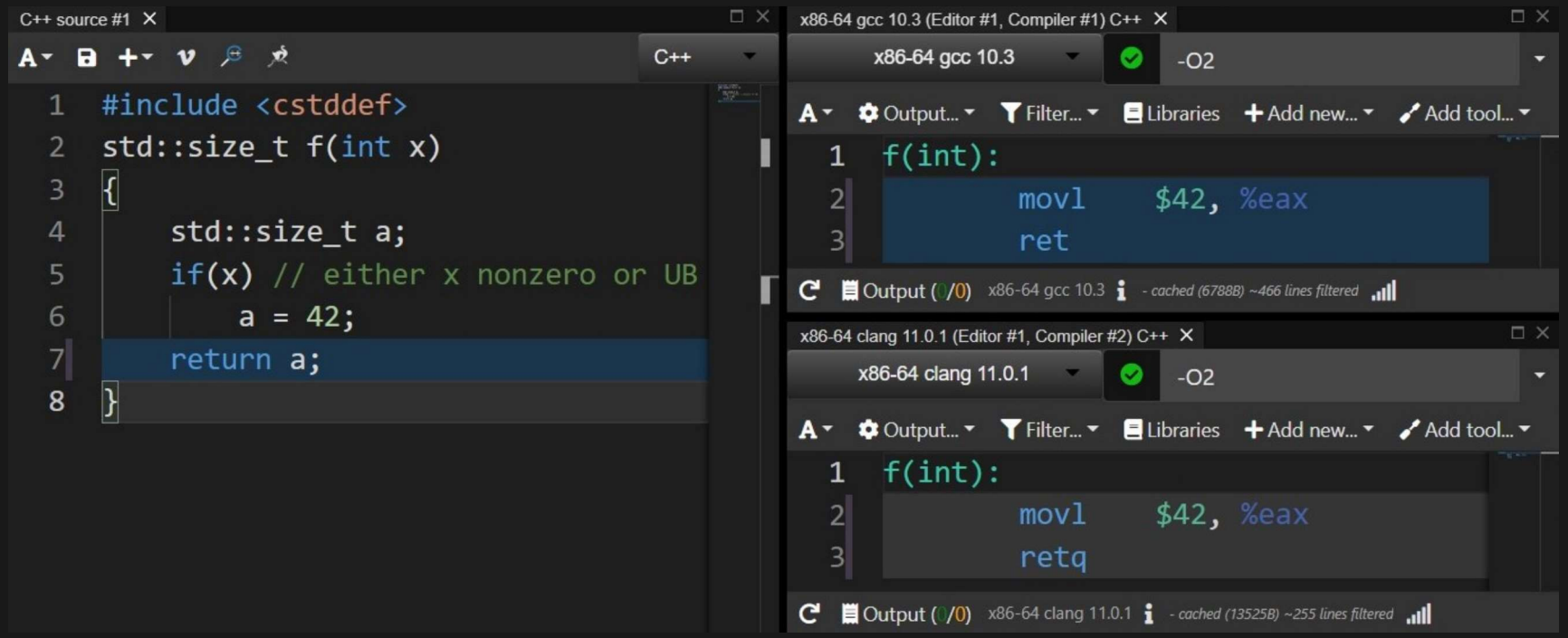
ALGEBRAIC IDENTITIES

DEAD CODE ELIMINATION

CONSTANT FOLDING

OPTIMIZATIONS AND SEMANTICS

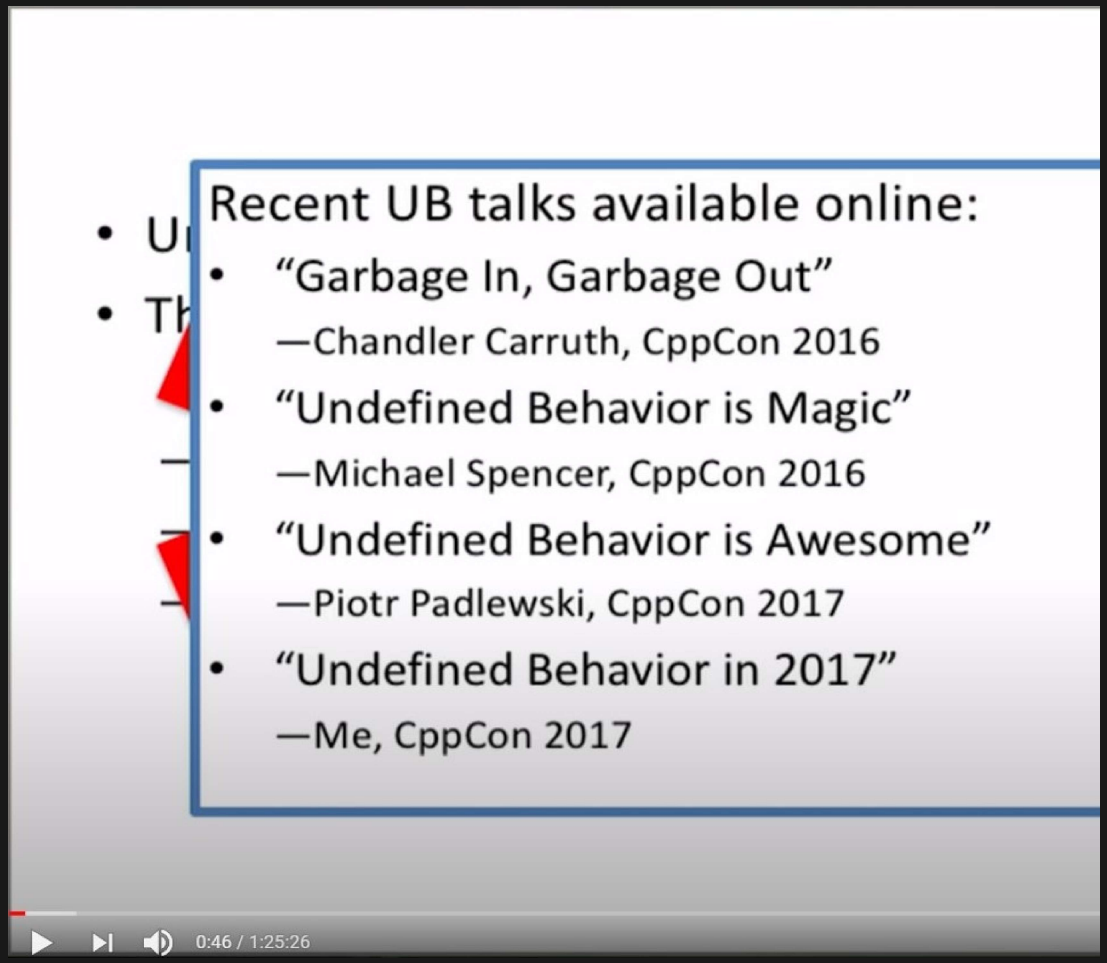
Cppreference UB examples



OPTIMIZATIONS AND SEMANTICS

REFINE

OPTIMIZATIONS AND SEMANTICS



LVN DEMO

```
> cat tests/lvn_dce.bril
# CMD: bril2json < {filename} | python3 ../lvn.py | python3 ../dce.py | bril2txt
@main {
  a: int = const 6;
  a: int = const 4;
  b: int = const 2;
  sum1: int = add a b;
  sum2: int = add b a;
  prod: int = mul sum1 sum2;
  print prod;
  x: int = const 4;
  copy1: int = id x;
  copy2: int = id copy1;
  copy3: int = id copy2;
  print copy3;
  c: int = const 5;
  sum1: int = add c b;
  prod2: int = mul sum1 sum2;
}
```

LVN DEMO

```
> cat tests/lvn_dce.bril | bril2json | python3 lvn.py | python3 dce.py | bril2txt
@main {
  a#1: int = const 4;
  prod: int = const 36;
  print prod;
  print a#1;
}
```

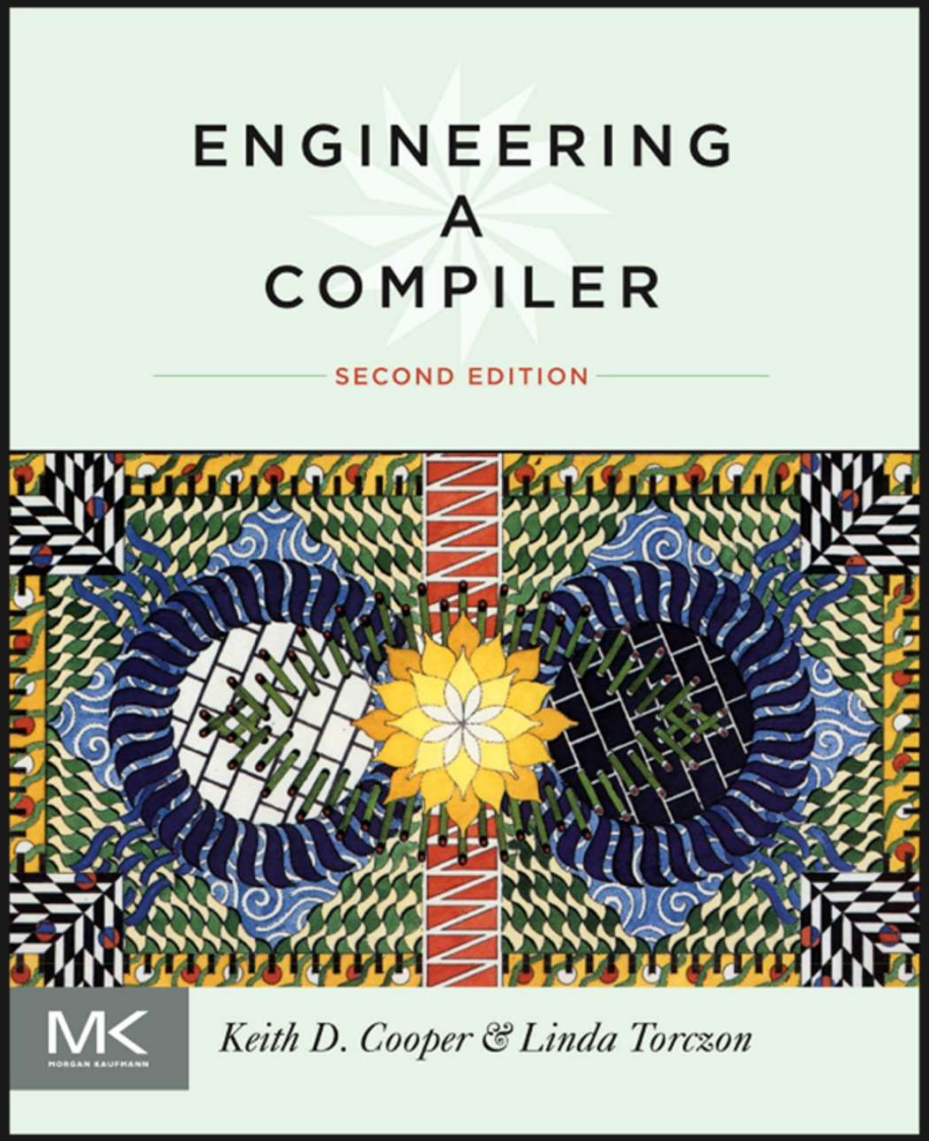
LVN DEMO

```
> cloc lvn.py
       1 text file.
       1 unique file.
       0 files ignored.

github.com/AlDanial/cloc v 1.82  T=0.01 s (172.3 files/s, 36009.3 lines/s)
-------------------------------------------------------------------------------
Language                     files          blank        comment           code
-------------------------------------------------------------------------------
Python                           1             39             22            148
-------------------------------------------------------------------------------
```

LVN DEMO

```
> cloc dce.py
       1 text file.
       1 unique file.
       0 files ignored.

github.com/AlDanial/cloc v 1.82  T=0.00 s (233.1 files/s, 17948.3 lines/s)
-------------------------------------------------------------------------------
Language                     files          blank        comment           code
-------------------------------------------------------------------------------
Python                           1             14             15             48
-------------------------------------------------------------------------------
```

WHERE TO LEARN MORE



Cornell CS 6120, self-guided online course, Lesson 3

LLVM's Global Value Numbering pass

Introducing a new, advanced Visual C++ code optimizer

RECAPPING VALUE NUMBERING

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- Redundancy everywhere

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- VN is effective

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- Algebraic identities are important

RECAPPING VALUE NUMBERING

- Redundancy everywhere
- VN is effective
- Algebraic identities are important
- Don't have to be a rock star to implement it

CONCLUSIONS

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- Compilers are full of marvels

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CONCLUSIONS

- Compilers are full of marvels
- It is not black magic, it can be understood
- You can easily start to experiment
- Simple albeit beautiful math can go a long way
- You do not need to help the compiler (mostly)

Q&A