Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-16/

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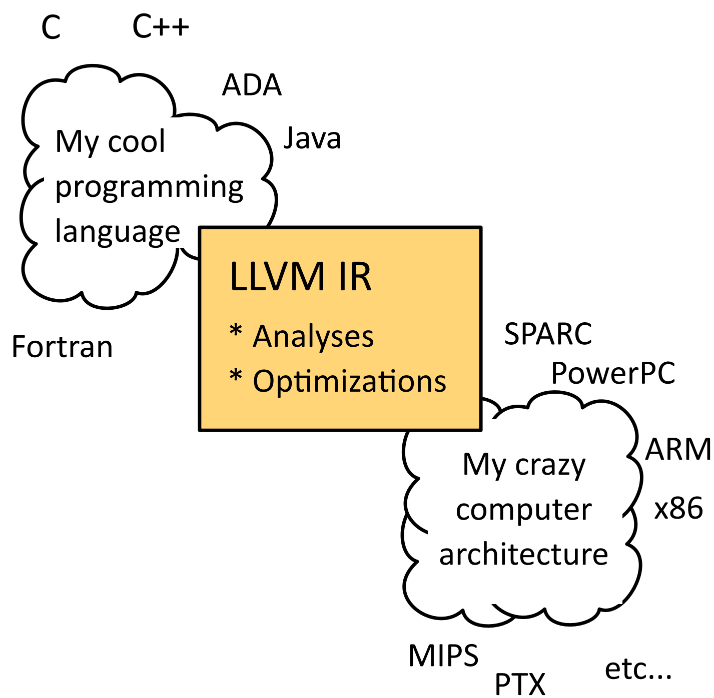
Lesson 13

- A Quick Intro to LLVM

What is LLVM?

LLVM is a compiler infrastructure designed as a set of reusable libraries with well-defined interfaces [*Wikipedia*]:

- Implemented in C++
- Several front-ends
- Several back-ends
- First release: 2003
- Open source
- http://llvm.org/



LLVM is a Compilation Infra-Structure

- It is a framework that comes with lots of tools to compile and optimize code.

```
$> cd llvm/Debug+Asserts/bin
$> ls
FileCheck         count              llvm-dis          llvm-stress
FileUpdate        diagtool           llvm-dwarfdump    llvm-symbolizer
arcmt-test        fpcmp              llvm-extract      llvm-tblgen
bugpoint          llc                llvm-link         macho-dump
c-arcmt-test      lli                llvm-lit          modularize
c-index-test      lli-child-target   llvm-lto          not
clang             llvm-PerfectSf     llvm-mc           obj2yaml
clang++           llvm-ar            llvm-mcmarkup     opt
llvm-as           llvm-nm            pp-trace          llvm-size
clang-check       llvm-bcanalyzer    llvm-objdump      rm-cstr-calls
clang-format      llvm-c-test        llvm-ranlib       tool-template
clang-modernize   llvm-config        llvm-readobj      yaml2obj
clang-tblgen      llvm-cov           llvm-rtdyld       llvm-diff
clang-tidy
```

LLVM is a Compilation Infra-Structure

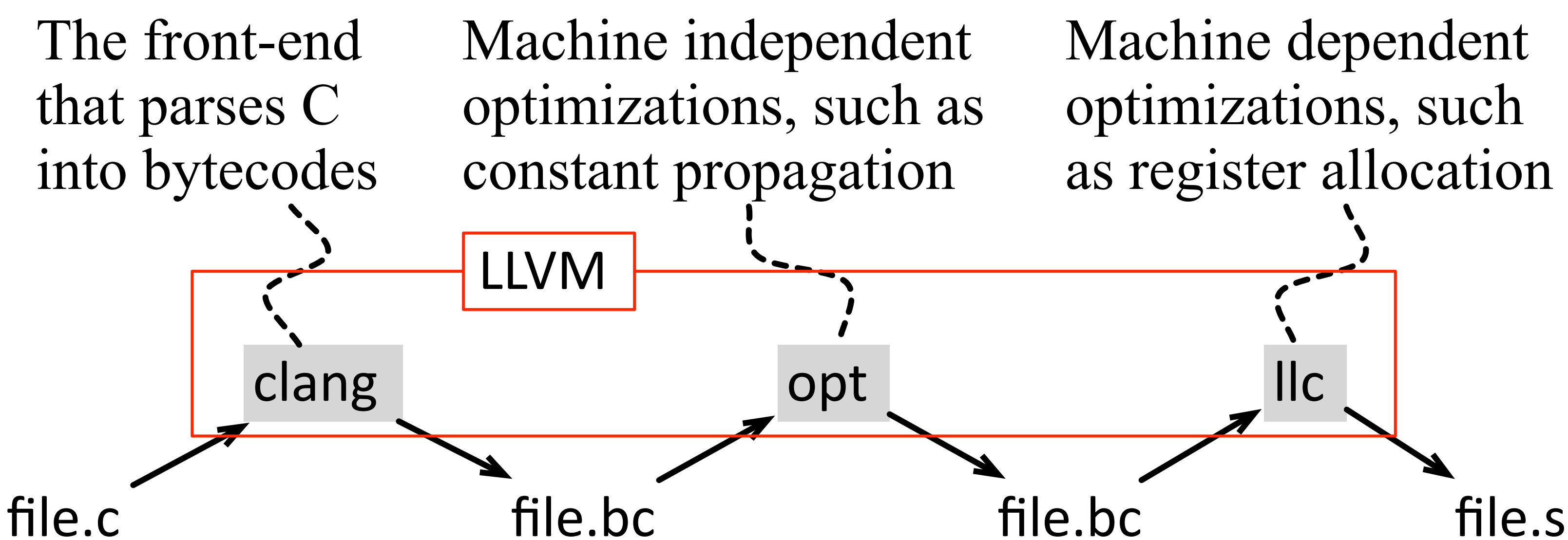
- Compile C/C++ programs:

```
$> echo "int main() {return 42;}" > test.c
$> clang test.c
$> ./a.out
$> echo $?
42
```

clang/clang++ are very competitive when compared with, say, gcc, or icc. Some of these compilers are faster in some benchmarks, and slower in others. Usually clang/clang++ have faster compilation times. The Internet is crowded with benchmarks.

Optimizations in Practice

- The **opt** tool, available in the LLVM toolbox, performs machine independent optimizations.
- There are many optimizations available through opt.
  - To have an idea, type `opt --help`.



Optimizations in Practice

```
$> opt --help
  Optimizations available:
    -adce                        - Aggressive Dead Code Elimination
    -always-inline               - Inliner for always_inline functions
    -break-crit-edges            - Break critical edges in CFG
    -codegenprepare              - Optimize for code generation
    -constmerge                  - Merge Duplicate Global Constants
    -constprop                   - Simple constant propagation
    -correlated-propagation      - Value Propagation
    -dce                         - Dead Code Elimination
    -deadargelim                 - Dead Argument Elimination
    -die                         - Dead Instruction Elimination
    -dot-cfg                     - Print CFG of function to 'dot' file
    -dse                         - Dead Store Elimination
    -early-cse                   - Early CSE
    -globaldce                   - Dead Global Elimination
    -globalopt                   - Global Variable Optimizer
    -gvn                         - Global Value Numbering
    -indvars                     - Induction Variable Simplification
    -instcombine                 - Combine redundant instructions
    -instsimplify                - Remove redundant instructions
    -ipconstprop                 - Interprocedural constant propagation
    -loop-reduce                 - Loop Strength Reduction
    -reassociate                 - Reassociate expressions
    -reg2mem                     - Demote all values to stack slots
    -sccp                        - Sparse Conditional Constant Propagation
    -scev-aa                     - ScalarEvolution-based Alias Analysis
    -simplifycfg                 - Simplify the CFG
    ...
```

Levels of Optimizations

- Like gcc, clang supports different levels of optimizations, e.g., -O0 (default), -O1, -O2 and -O3.
- To find out which optimization each level uses, you can try:

llvm-as is the LLVM assembler. It reads a file containing human-readable LLVM assembly language, translates it to LLVM bytecode, and writes the result into a file or to standard output.

```
$> llvm-as < /dev/null | opt -O3 -disable-output -debug-pass=Arguments
```

Example of output for –O1:

-targetlibinfo -no-aa -tbaa -basicaa -notti -globalopt -ipsccp -deadargelim -instcombine -simplifycfg -basiccg -prune-eh -inline-cost -always-inline -functionattrs -sroa -domtree -early-cse -lazy-value-info -jump-threading -correlated-propagation -simplifycfg -instcombine -tailcallelim -simplifycfg -reassociate -domtree -loops -loop-simplify -lcssa -loop-rotate -licm -lcssa -loop-unswitch -instcombine -scalar-evolution -loop-simplify -lcssa -indvars -loop-idiom -loop-deletion -loop-unroll -memdep -memcpyopt -sccp -instcombine -lazy-value-info -jump-threading -correlated-propagation -domtree -memdep -dse -adce -simplifycfg -instcombine -strip-dead-prototypes -preverify -domtree -verify

Virtual Register Allocation

- One of the most basic optimizations that opt performs is to map memory slots into register.
- This optimization is very useful, because the clang front end maps every variable to memory:

```c
int main() {
  int c1 = 17;
  int c2 = 25;
  int c3 = c1 + c2;
  printf("Value = %d\n", c3);
}
```

```
$> clang -c -emit-llvm const.c -o const.bc

$> opt –view-cfg const.bc
```

```
%0:
 %1 = alloca i32, align 4
 %c1 = alloca i32, align 4
 %c2 = alloca i32, align 4
 %c3 = alloca i32, align 4
 store i32 0, i32* %1
 store i32 17, i32* %c1, align 4
 store i32 25, i32* %c2, align 4
 %2 = load i32* %c1, align 4
 %3 = load i32* %c2, align 4
 %4 = add nsw i32 %2, %3
 store i32 %4, i32* %c3, align 4
 %5 = load i32* %c3, align 4
 %6 = call @printf(...)
 %7 = load i32* %1
 ret i32 %7
```

CFG for 'main' function

Virtual Register Allocation

- One of the most basic optimizations that opt performs is to map memory slots into variables.
- We can map memory slots into registers with the `mem2reg` pass:

```
int main() {
  int c1 = 17;
  int c2 = 25;
  int c3 = c1 + c2;
  printf("Value = %d\n", c3);
}
```

How could we further optimize this program?

```
$> opt -mem2reg const.bc > const.reg.bc

$> opt –view-cfg const.reg.bc
```

```
%0:
 %1 = add nsw i32 17, 25
 %2 = call @printf(...), i32 %1)
 ret i32 0
```

CFG for 'main' function

Constant Propagation

- We can fold the computation of expressions that are known at compilation time with the `constprop` pass.

```
%0:
 %1 = add nsw i32 17, 25
 %2 = call @printf(...), i32 %1)
 ret i32 0
```

CFG for 'main' function

→

```
%0:
 %1 = call i32 (i8*, ...)* @printf(..., i32 42)
 ret i32 0
```

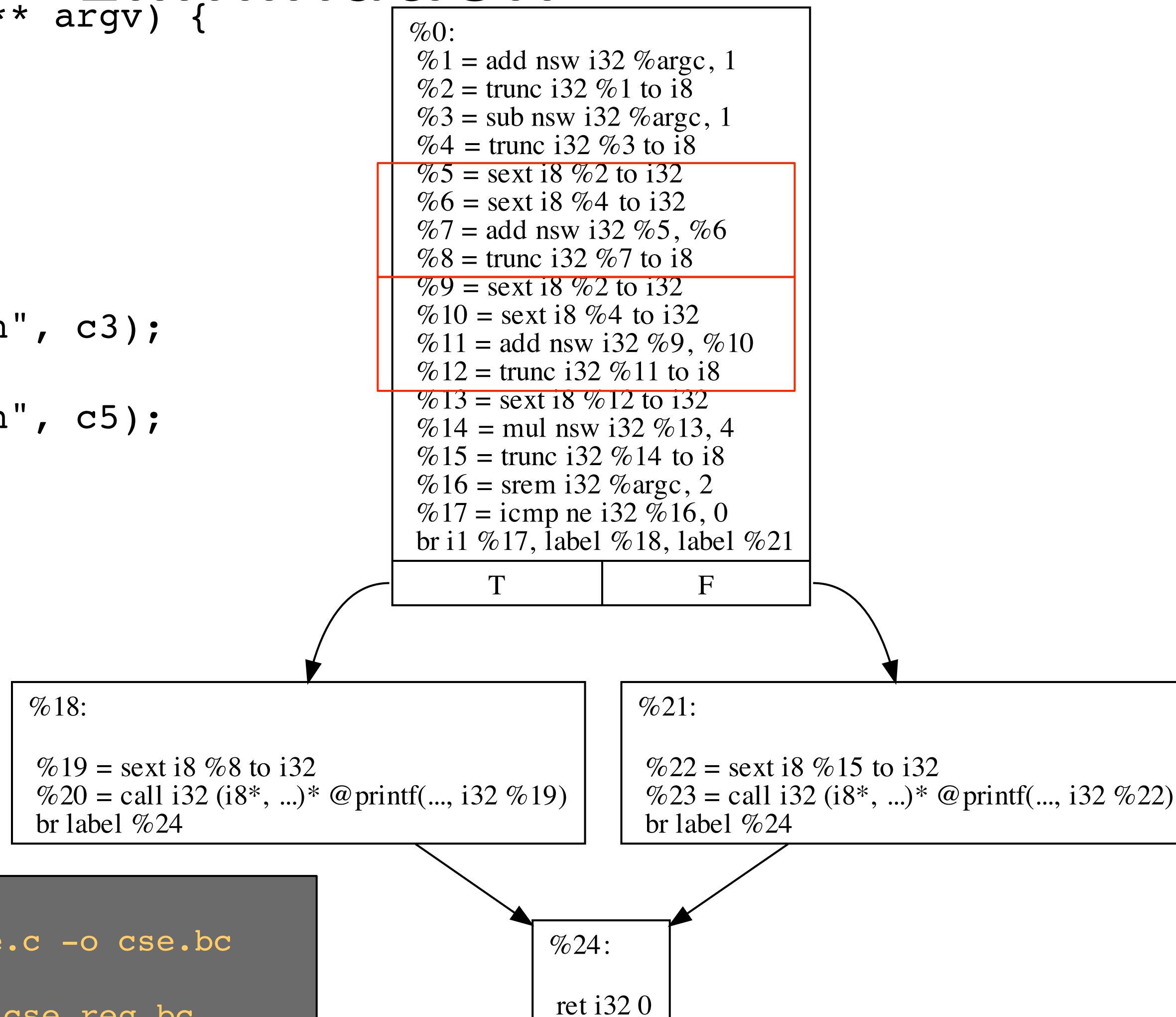
CFG for 'main' function

```
$> opt -constprop const.reg.bc > const.cp.bc

$> opt –view-cfg const.cp.bc
```

What is %1 in the left CFG? And what is i32 42 in the CFG on the right side?

One more: Common Subexpression Elimination

```
int main(int argc, char** argv) {
  char c1 = argc + 1;
  char c2 = argc - 1;
  char c3 = c1 + c2;
  char c4 = c1 + c2;
  char c5 = c4 * 4;
  if (argc % 2)
    printf("Value = %d\n", c3);
  else
    printf("Value = %d\n", c5);
}
```

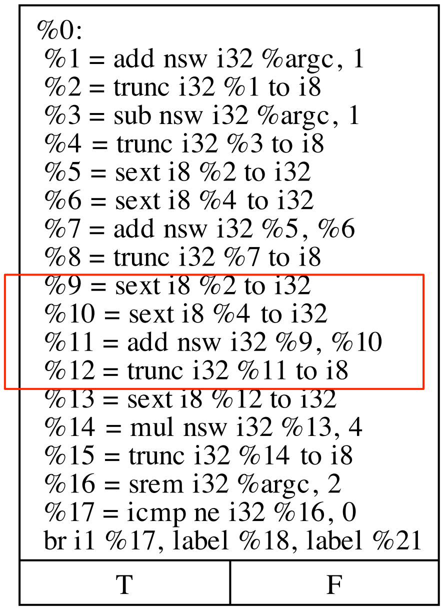


CFG for 'main' function

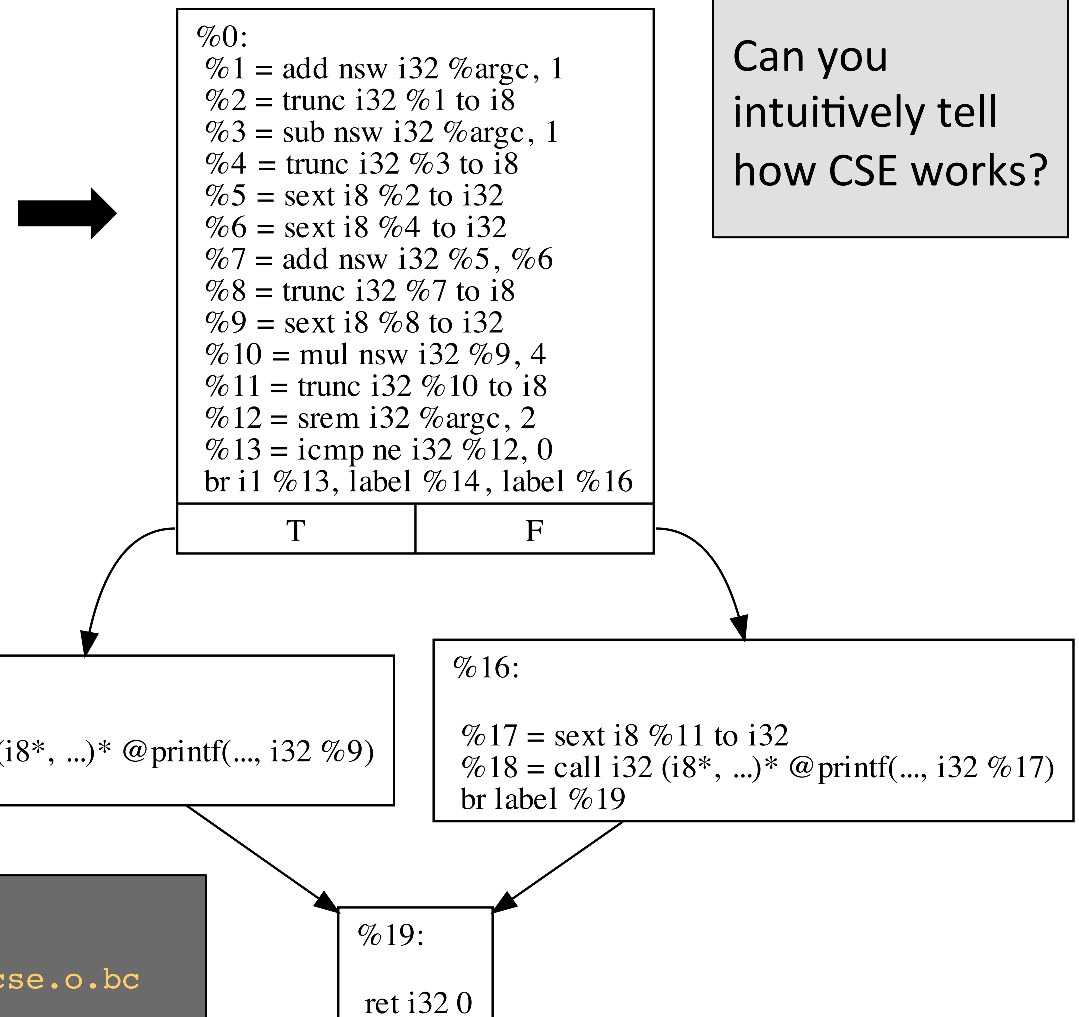
How could we optimize this program?

```
$> clang -c -emit-llvm cse.c -o cse.bc

$> opt –mem2reg cse.bc -o cse.reg.bc

$> opt –view-cfg cse.reg.bc
```

One more: Common Subexpression Elimination



Original Basic Block



CFG for 'main' function

Can you intuitively tell how CSE works?

```
$> opt -early-cse cse.reg.bc > cse.o.bc

$> opt —view-cfg cse.o.bc
```

LLVM Provides an IR

- LLVM represents programs, internally, via its own instruction set.
  - The LLVM optimizations manipulate these bytecodes.
  - We can program directly on them.
  - We can also interpret them.

♤

```
int callee(const int* X) {
  return *X + 1;
}

int main() {
  int T = 4;
  return callee(&T);
}
```

```
$> clang –c –emit-llvm f.c –o f.bc

$> opt –mem2reg f.bc –o f.bc

$> llvm-dis f.bc

$> cat f.ll
```

```
; Function Attrs: nounwind ssp
define i32 @callee(i32* %X) #0 {
entry:
  %0 = load i32* %X, align 4
  %add = add nsw i32 %0, 1
  ret i32 %add
}
```

♤: Example taken from the slides of Gennady Pekhimenko "The LLVM Compiler Framework and Infrastructure"

LLVM Bytecodes are Interpretable

- Bytecode is a form of instruction set designed for efficient execution by a software interpreter.
  - They are portable!
  - Example: Java bytecodes.
- The tool **lli** directly executes programs in LLVM bitcode format.
  - lli may compile these bytecodes just-in-time, if a JIT is available.

```
$> echo "int main() {printf(\"Oi\n\");}" > t.c

$> clang -c -emit-llvm t.c -o t.bc

$> lli t.bc
```

How Does the LLVM IR Look Like?

- RISC instruction set, with typical opcodes
  - add, mul, or, shift, branch, load, store, etc
- Typed representation.

```
%0 = load i32* %X, align 4
%add = add nsw i32 %0, 1
ret i32 %add
```

- Static Single Assignment format
- Control flow is represented explicitly.

<u>This is C</u>

```
switch(argc) {
  case 1: x = 2;
  case 2: x = 3;
  case 3: x = 5;
  case 4: x = 7;
  case 5: x = 11;
  default: x = 1;
}
```

<u>This is LLVM</u>

```
switch i32 %0, label %sw.default [
  i32 1, label %sw.bb
  i32 2, label %sw.bb1
  i32 3, label %sw.bb2
  i32 4, label %sw.bb3
  i32 5, label %sw.bb4
]
```

Generating Machine Code

- Once we have optimized the intermediate program, we can translate it to machine code.
- In LLVM, we use the llc tool to perform this translation. This tool is able to target many different architectures.

```
$> llc --version

  Registered Targets:
    alpha      - Alpha [experimental]
    arm        - ARM
    bfin       - Analog Devices Blackfin
    c          - C backend
    cellspu    - STI CBEA Cell SPU
    cpp        - C++ backend
    mblaze     - MBlaze
    mips       - Mips
    mips64     - Mips64 [experimental]
    mips64el   - Mips64el [experimental]
    mipsel     - Mipsel
    msp430     - MSP430 [experimental]
    ppc32      - PowerPC 32
    ppc64      - PowerPC 64
    ptx32      - PTX (32-bit) [Experimental]
    ptx64      - PTX (64-bit) [Experimental]
    sparc      - Sparc
    sparcv9    - Sparc V9
    systemz    - SystemZ
    thumb      - Thumb
    x86        - 32-bit X86: Pentium-Pro
    x86-64     - 64-bit X86: EM64T and AMD64
    xcore      - XCore
```

Generating Machine Code

- Once we have optimized the intermediate program, we can translate it to machine code.
- In LLVM, we use the llc tool to perform this translation. This tool is able to target many different architectures.

```
$> clang -c -emit-llvm identity.c -o identity.bc

$> opt -mem2reg identity.bc -o identity.opt.bc

$> llc -march=x86 identity.opt.bc -o identity.x86
```

```
        .globl      _identity
        .align      4, 0x90
_identity:
        pushl %ebx
        pushl %edi
        pushl %esi
        xorl  %eax, %eax
        movl  20(%esp), %ecx
        movl  16(%esp), %edx
        movl  %eax, %esi
        jmp   LBB1_1
        .align      4, 0x90
LBB1_3:
        movl  (%edx,%esi,4), %ebx
        movl  $0, (%ebx,%edi,4)
        incl  %edi
LBB1_2:
        cmpl  %ecx, %edi
        jl    LBB1_3
        incl  %esi
LBB1_1:
        cmpl  %ecx, %esi
        movl  %eax, %edi
        jl    LBB1_2
        jmp   LBB1_5
LBB1_6:
        movl  (%edx,%eax,4), %esi
        movl  $1, (%esi,%eax,4)
        incl  %eax
LBB1_5:
        cmpl  %ecx, %eax
        jl    LBB1_6
        popl  %esi
        popl  %edi
        popl  %ebx
        ret
```