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12/19/08

COMS W4115 – Final report
C Flat / ltc

Introduction

The C Flat language is mostly a subset of the C language. Some of the core functionalities of C has been stripped: there is no preprocessor, no structs, no strings, not even pointers. It's goal is purely educational.

Originally Nico and Dan were working on two separate languages. The two projects merged, taking some features from each, and this is the resulting language.

The ltc and C Flat language proposals are included in appendix A.

C Flat Tutorial

C Flat is easy to use for any programmer familiar with a C-like language. The main differences from C are that there is only one type: the integer, variables don't have to be declared before use (but there are no global variables), and there are exceptions.

"Hello World" (outputs 1):

```
main() {
	out(1);
}
```

Recursive Fibonacci:

```
fib(n) {
	if (n < 3) return 1;
	else return fib(n-1) + fib(n-2);
}
main() {
	out(fib(in()));
}
```

Iterative Fibonacci:

```
fib(n) {
	if (n < 1)
		throw 1;

	a = 1; // last fib #
	b = 1; // current fib #
	for (i = 3; i <= n; i++) {
		temp = b;
		b += a;
		a = temp;
	}
	return b;
}
main() {
	out(fib(in()));
}
```

Language Manual

The LRM is included in appendix B.

Project Plan

Processes

When we merged projects, we decided to start off by implementing as much of the ltc proposal as possible and adding features from the original c flat proposal at the end if we had time. The ltc proposal clearly laid out the subset of C which we would be implementing. Since we were basing the language off of an existing one, there wasn't very much planning that had to go into figuring out how the language would work as far as the users are concerned.

Our process for progressing through the project was to pick a feature that wasn't implemented and think through how exactly it should work and how it needed to be implemented. We sometimes had to compile some test C programs and look at the assembly generated or look up instructions in the Intel x86 manuals to learn exactly how something would work. Then we'd implement the feature and some tests for it. Sometimes we wrote the corresponding part of the LRM at that point and sometimes we filled it in later. This normally wouldn't be a great idea, but this language is small enough that it worked just fine.

We had an automated tester which would run a series of code snippets through the compiler, run them, and verify that the output (or lack thereof) was correct. The tester was an improved version of the tester Dan used last fall in PLT. Initially we were also running the test suite that professor Edwards supplied with microc, but we eventually migrated to only our tester. It was quicker and easier to write tests for this tester because they all go in one file. After we did any work on the compiler, we'd run a quick "make test" and be able to verify that everything still worked correctly.

Programming Style Guide

For the compiler, we stuck with the style already used in microc. More or less:

- Indentation: 2 spaces.
- Indentation level is increased when declaring a non trivial function (that is a function with at least one argument)
- When matching, each case should be on it's own line. It also increase the indentation level.
- Function names are in lower case with words separated by underscores.
- Structures: names and fields are lower case with works separated by underscores.
- Types: names lowercase, possible values first letter uppercase.
- Tester uses standard python style as outlined in PEP 8 - http://www.python.org/dev/peps/pep-0008/
- Tests: lower case variables and functions, 2 space indentation.

For example, this is a snippet from backend.ml:

```
let rec eval_expr_to_eax fdecl = function
    Literal(l) ->
      sprintf "mov eax, %d\n" l

  | Assignop(v, o, e) ->
      let assign_binop binop =
        eval_expr_to_eax fdecl (Assignop(v, Assign, Binop(Id(v), binop, e))) in
      (match o with
          Assign       -> eval_expr_to_eax fdecl e ^
                            sprintf "mov [ebp+%d], eax\n" (id_to_offset fdecl v)
        | Add_assign    -> assign_binop Add
        | Sub_assign    -> assign_binop Sub
        | Mult_assign   -> assign_binop Mult
        | Div_assign    -> assign_binop Div
```

Project Timeline

- October: Proposals, automated tester.
- November: Merged projects, first assembly program generated (skeleton, functions, basic operators, I/O, if, for, and while), LRM started.
- December:
  - Week 1: Nothing.
  - Week 2: Many operators, proper argument evaluation, break, continue, exceptions.
  - Week 3: Static semantic analysis, compiler completed, LRM completed.

Roles and Responsibilities

We worked together on most aspects of the project. Nico implemented a number of language features on his own and Dan got the automated tester going.

Software Development Environment

We are both running a linux OS with its standard tools.

Kate, Vim, and Nano	Source code editing
Ocaml Tool Suite	Lexer, parser, static and semantic analysis, backend, top level compiler driver
Gcc	Compiling standard library (which is C), assembling output of the C Flat compiler, linking object files
Python	Automated tester
OpenOffice	Report
Lyx	LRM
GNU Make	Project building

Project Log

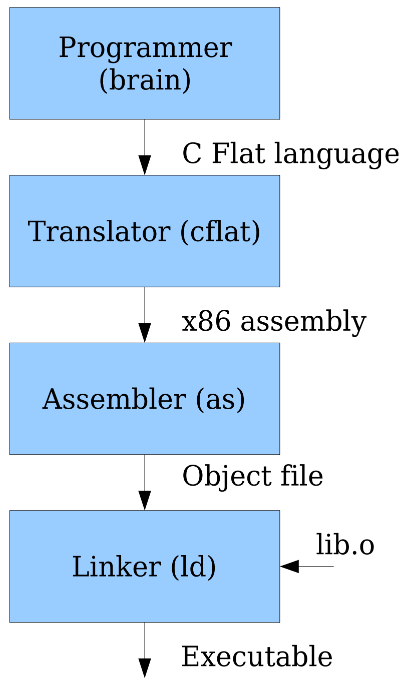
We used git as a version control system. The project history is:

Nicolas Viennot	2008-12-18 10:47:49 -0500	style fix
Nicolas Viennot	2008-12-18 10:45:37 -0500	style fix
Nicolas Viennot	2008-12-18 10:39:08 -0500	style fix
Nicolas Viennot	2008-12-18 10:01:23 -0500	lrm updated
Nicolas Viennot	2008-12-18 08:37:28 -0500	removed dead code
Nicolas Viennot	2008-12-18 08:34:34 -0500	not pushing esp for exception
Nicolas Viennot	2008-12-17 21:44:26 -0500	added test for shifting negative number
Nicolas Viennot	2008-12-17 18:03:25 -0500	removed the goto keyword
Nicolas Viennot	2008-12-17 16:45:58 -0500	added if/else test (2)
Nicolas Viennot	2008-12-17 16:44:52 -0500	added if/else test
Daniel Benamy	2008-12-17 16:05:22 -0500	Merge branch 'work'
Daniel Benamy	2008-12-17 16:05:00 -0500	Renamed microc to cflat.
Nicolas Viennot	2008-12-17 16:01:14 -0500	Assign is not an assignop
Daniel Benamy	2008-12-17 15:54:58 -0500	Added a couple of tests for exceptions.
Nicolas Viennot	2008-12-17 15:48:23 -0500	precedence change for < >
Daniel Benamy	2008-12-17 15:47:16 -0500	Print compiler errors to stderr.
Nicolas Viennot	2008-12-17 15:35:01 -0500	unclosed comment raise exception
Nicolas Viennot	2008-12-16 19:51:18 -0500	cleanup
Nicolas Viennot	2008-12-16 12:37:58 -0500	asm test pretty
Nicolas Viennot	2008-12-16 12:33:02 -0500	small asm change
Nicolas Viennot	2008-12-16 08:37:29 -0500	added .PHONY : test/clean in Makefile
Nicolas Viennot	2008-12-15 20:45:41 -0500	sast: checking for duplicated function, duplicated formals. test: testing for local variable discovery and duplicates.
Nicolas Viennot	2008-12-15 20:09:35 -0500	sast: forgot a variable check
Nicolas Viennot	2008-12-15 20:07:04 -0500	cleanup
Nicolas Viennot	2008-12-15 20:03:59 -0500	sast: variables are added through the context struct
Nicolas Viennot	2008-12-15 19:44:13 -0500	cleanup
Nicolas Viennot	2008-12-15 14:42:54 -0500	cleanup
Nicolas Viennot	2008-12-15 14:14:57 -0500	removed test directory
Nicolas Viennot	2008-12-15 14:08:45 -0500	removing old tests
Nicolas Viennot	2008-12-15 14:06:09 -0500	more tests
Nicolas Viennot	2008-12-15 12:10:25 -0500	cleanup
Nicolas Viennot	2008-12-15 12:10:15 -0500	added test when mixing same function name/variable name
Nicolas Viennot	2008-12-15 12:09:25 -0500	catch exception on syntax error
Nicolas Viennot	2008-12-15 10:41:14 -0500	ast printer removed
Nicolas Viennot	2008-12-15 10:38:39 -0500	local variables are now initialized to 0
Nicolas Viennot	2008-12-15 10:07:50 -0500	SAST added, local variables doesnt need to be declared anymore
Nicolas Viennot	2008-12-14 20:38:40 -0500	"uncaught exception" message added
Nicolas Viennot	2008-12-14 14:28:08 -0500	cleanup
Nicolas Viennot	2008-12-14 14:14:41 -0500	reversing args in function call is done is assembly
Nicolas Viennot	2008-12-14 13:37:41 -0500	precedence test added
Nicolas Viennot	2008-12-14 12:26:43 -0500	operator precedence fixed
Nicolas Viennot	2008-12-14 09:40:40 -0500	cleanup
Nicolas Viennot	2008-12-14 09:13:02 -0500	sign tests added for arithmetic binops
Nicolas Viennot	2008-12-14 09:12:45 -0500	using movzx insead of mov eax, 0
Nicolas Viennot	2008-12-13 16:33:28 -0500	cleanup
Nicolas Viennot	2008-12-13 15:14:11 -0500	exception implemented
Nicolas Viennot	2008-12-13 10:03:40 -0500	basic try/catch/throw implementation
Nicolas Viennot	2008-12-13 09:12:36 -0500	Operators implemented and tested
Nicolas Viennot	2008-12-13 07:43:56 -0500	comment scanner fixed
Nicolas Viennot	2008-12-13 07:32:01 -0500	arguments of a function are evaluated from left to right
Nicolas Viennot	2008-12-13 07:00:41 -0500	cleanup
Nicolas Viennot	2008-12-12 14:49:58 -0500	all operators added, exception added (not finished !!)
Nicolas Viennot	2008-12-12 09:20:40 -0500	added multiline comments
Nicolas Viennot	2008-12-12 09:12:31 -0500	reverted out() -> outputs \n and test programs are piped to xargs
Nicolas Viennot	2008-12-12 00:08:43 -0500	Added test for double variable declarations.Whitespace fix.
Nicolas Viennot	2008-12-12 00:06:55 -0500	Added lrm.
Nicolas Viennot	2008-12-11 23:07:12 -0500	Implemented proper labels for loops. Added break and continue keywords. Added tests.
Nicolas Viennot	2008-12-11 23:07:00 -0500	Removed interpreter.
Nicolas Viennot	2008-12-11 22:04:34 -0500	Implemented proper labels.Implemented in(). Changed out() to not add newline and added outln() and ln(). Fixed make test.
Nicolas Viennot	2008-12-11 22:04:02 -0500	Added .gitignore.
Nicolas Viennot	2008-12-11 20:25:43 -0500	removed test from make clean
Nicolas Viennot	2008-12-02 00:35:04 -0500	new test case, cleanup
Nicolas Viennot	2008-12-02 00:21:38 -0500	new test

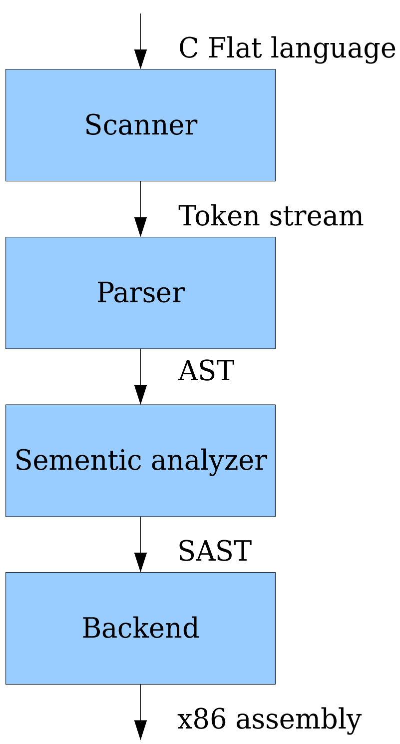
Nicolas Viennot	2008-12-02 00:18:13 -0500	global removed
Nicolas Viennot	2008-12-02 00:15:15 -0500	global tests removed
Nicolas Viennot	2008-12-02 00:12:32 -0500	okey whatever
Nicolas Viennot	2008-12-02 00:11:25 -0500	microc deleted
Daniel Benamy	2008-11-22 02:14:32 -0500	Added .gitignore.
Daniel Benamy	2008-11-22 02:11:46 -0500	Added ltc and microc. Started on a backend for microc to produce x86 assembly.
Daniel Benamy	2008-11-22 02:10:36 -0500	Put some skeleton file in cflat/, moved testing code to cflat/test, and added the very beginnings of a test file for c flat.
Daniel Benamy	2008-11-22 02:06:49 -0500	Fix crash when no executable is created.
Daniel Benamy	2008-10-16 02:49:59 -0400	Added hw1 dir.
Daniel Benamy	2008-10-16 01:24:07 -0400	Give nice error if no test file given.
Daniel Benamy	2008-10-16 00:39:13 -0400	Adding test-gcc.txt.
Daniel Benamy	2008-10-16 00:38:26 -0400	Changed test markers to ..., added support for comments before compilercommand, and cleanup.
Daniel Benamy	2008-10-16 00:24:50 -0400	Various fixes. Tester works.
Daniel Benamy	2008-10-16 00:09:09 -0400	Cleanup.
Daniel Benamy	2008-10-16 00:07:48 -0400	Importing compiler-tester.py in progress.

Architectural Design

Our translator receives a C Flat program and outputs the x86 assembly code:



The translator first tokenizes the character stream, parses it to generate an AST. Then the tree is semetically checked to produce a SAST which go through the backend to produce assembly code.



A few notes about the implementation:

- The sementic analyzer does the local variables discovery so that the backend knows in advance the stack size for local variables.
- Function calls: we follow the C convention that is: arguments are pushed in reverse order, and the caller cleans the stack. The register eax is used for return values.
- Exceptions: we use a linked list that is built on the stack. An element is added to the list when the program enters a try block. When an exception is thrown, it checks if the list is empty; if yes uncaught_exception() is called, if not it passes control to the catch block.
- Temporary values: during a complex expression evaluation, we use the stack to store temporary results.

Nico adapted the parser and the scanner from the microc code and implemented the sementic analyzer. Both Dan and Nico implemented the Backend.

Test Plan
Sample compilations

Recursive Fibonacci:

C Flat:

```
fib(n) {
        if (n < 0) throw -1;
        if (n < 3) return 1;
        else return fib(n-1) + fib(n-2);
}

main() {
        try {
                out(fib(in()));
        } catch(ex) {
                out(ex);
        }
}
```

Generated assembly:

```
.intel_syntax noprefix
.text
.globl main
.type main, @function
main:
push ebp
mov  ebp, esp
xor  eax, eax
push eax
push ecx
push edx
push ebp
push offset .L1
push dword ptr [__exception_ptr]
mov  [__exception_ptr], esp
call in
add  esp, 0
push eax
call fib
add  esp, 4
push eax
call out
add  esp, 4
mov eax, [__exception_ptr]
mov eax, [eax]
mov [__exception_ptr], eax
add  esp, 12
jmp .L2
.L1:
mov [ebp+-4], edx
mov eax, [ebp+-4]
push eax
call out
add  esp, 4
.L2:
.L0:
```

```
pop  edx
pop  ecx
mov  esp, ebp
pop  ebp
ret
.globl fib
.type fib, @function
fib:
push ebp
mov  ebp, esp
xor  eax, eax
push ecx
push edx
mov eax, [ebp+8]
push eax
mov eax, 0
pop  ecx
xchg eax, ecx
cmp eax, ecx
setl  al
movzx eax, al
test eax, eax
jz   .L4
mov eax, 1
neg   eax
mov  edx, eax
mov  ecx, [__exception_ptr]
test ecx, ecx
jnz  .L6
push edx
call __uncaught_exception
.L6:
mov eax, [__exception_ptr]
mov eax, [eax]
mov [__exception_ptr], eax
lea  esp, [ecx+12]
mov  ebp, [ecx+8]
jmp  [ecx+4]
jmp  .L5
.L4:
.L5:
mov eax, [ebp+8]
push eax
mov eax, 3
pop  ecx
xchg eax, ecx
cmp eax, ecx
setl  al
movzx eax, al
test eax, eax
jz   .L7
add  esp, 0
mov eax, 1
jmp .L3
jmp  .L8
.L7:
add  esp, 0
mov eax, [ebp+8]
```

```
push eax
mov eax, 1
pop  ecx
xchg eax, ecx
sub   eax, ecx
push eax
call fib
add  esp, 4
push eax
mov eax, [ebp+8]
push eax
mov eax, 2
pop  ecx
xchg eax, ecx
sub   eax, ecx
push eax
call fib
add  esp, 4
pop  ecx
xchg eax, ecx
add   eax, ecx
jmp .L3
.L8:
.L3:
pop  edx
pop  ecx
mov  esp, ebp
pop  ebp
ret
.ident "C Flat compiler 0.1"
```

GCD:

C Flat:

```
gcd(a, b) {
        while (a != b) {
                if (a > b) a -= b;
                else b -= a;
        }
        return a;
}

main() {
        a = in();
        b = in();
        out(gcd(a, b));
}
```

Generated assembly:

```
.intel_syntax noprefix
.text
.globl main
.type main, @function
main:
push ebp
mov  ebp, esp
xor  eax, eax
push eax
push ecx
push edx
push ebp
push offset .L1
push dword ptr [__exception_ptr]
mov  [__exception_ptr], esp
call in
add  esp, 0
push eax
call fib
add  esp, 4
push eax
call out
add  esp, 4
mov eax, [__exception_ptr]
mov eax, [eax]
mov [__exception_ptr], eax
add  esp, 12
jmp .L2
.L1:
mov [ebp+-4], edx
mov eax, [ebp+-4]
push eax
call out
add  esp, 4
.L2:
.L0:
pop  edx
pop  ecx
mov  esp, ebp
pop  ebp
```

```
ret
.globl fib
.type fib, @function
fib:
push ebp
mov  ebp, esp
xor  eax, eax
push ecx
push edx
mov eax, [ebp+8]
push eax
mov eax, 0
pop  ecx
xchg eax, ecx
cmp eax, ecx
setl  al
movzx eax, al
test eax, eax
jz   .L4
mov eax, 1
neg   eax
mov  edx, eax
mov  ecx, [__exception_ptr]
test ecx, ecx
jnz  .L6
push edx
call __uncaught_exception
.L6:
mov eax, [__exception_ptr]
mov eax, [eax]
mov [__exception_ptr], eax
lea  esp, [ecx+12]
mov  ebp, [ecx+8]
jmp  [ecx+4]
jmp  .L5
.L4:
.L5:
mov eax, [ebp+8]
push eax
mov eax, 3
pop  ecx
xchg eax, ecx
cmp eax, ecx
setl  al
movzx eax, al
test eax, eax
jz   .L7
add  esp, 0
mov eax, 1
jmp .L3
jmp  .L8
.L7:
add  esp, 0
mov eax, [ebp+8]
push eax
mov eax, 1
pop  ecx
xchg eax, ecx
```

```
sub   eax, ecx
push eax
call fib
add  esp, 4
push eax
mov eax, [ebp+8]
push eax
mov eax, 2
pop  ecx
xchg eax, ecx
sub   eax, ecx
push eax
call fib
add  esp, 4
pop  ecx
xchg eax, ecx
add   eax, ecx
jmp .L3
.L8:
.L3:
pop  edx
pop  ecx
mov  esp, ebp
pop  ebp
ret
.ident "C Flat compiler 0.1"
```

Test suite

Our tester is a small python program which parses a text file with a very simple format, runs the test cases it finds, and verifies that the correct result is produced. See appendix C for the tester code (tester.py).

Test cases

Each feature of the compiler is tested. During the developement, when we added a feature, we wrote a test case for it to validate the implementation. At least one test case is written for each specification of the LRM.
See appendix C for test cases (test-cflat.txt).

Automation

A simple “make test” rebuilds the compiler if needed and executes all test cases. Making the test process very accessible is important since we use a test-driven development

Division of Testing Work

Dan wrote the automated tester. We wrote tests as we were adding features so we wrote a number of tests together, mainly checking things in microc. Then when Nico implemented all the additional operators, exceptions, and static semantic analysis, he wrote most of the tests for those.

Lessons Learned

Dan learned that Ocaml is pretty cool. Functional programming takes getting used to, and this project was a bunch of getting-used-to-ness.

Nico learned that Ocaml is a very nice language and that compilers are not magical anymore.

We would strongly encourage future teams to do automated testing and add test cases for each feature before or at roughly the same time as the feature it's testing. In addition to serving as a verification of functionality and preventing regressions, the act of writing code in the new language helps with figuring out how things should work and can bring up odd cases that might otherwise go unnoticed.

We recommend that teams reuse our tester since it lowers the effort required to add tests to about as low as possible.

Appendix A – Language proposals

Cb (C flat)

Daniel Benamy

Introduction
This is the language proposal for a new language, Cb (pronounced "see flat"). It is not intended to be a complete language reference manual, although it may morph into one.

Cb is a toy language which I'm using to learn how to write a compiler in OCaml. It contains a basic subset of C with some additions, including functions as first class types, and exceptions.

Target
Will compile to C.

Whitespace
Will use python-style nesting via indentation. The start of a block will end with a ':' and each level of nesting is indicated by indenting 4 spaces. Newlines are statement separators. Any number of spaces, including zero, are allowed around identifiers and punctuation.

Comments
C and C++ style comments allowed.
    // I am a single line comment.
    / I am a multi-line comment. */*
Multi-line comments end with the first */ found.

Control Flow
Control flow is achieved using functions, if statements, while statements, and exceptions.

Control starts in the main function which must exist. It doesn't take any arguments and must return an int.
    int main():
        return 0

Types
int, float (implemented as a double), char, bool, func.

Func is a multi-type. The types that the funtion takes and returns must be specified.
    func{int; int, int} f // Declares a variable f which is a function that takes two ints and returns an int.

Operators
This table lists the available operators and what types they take as arguments. All operators return the same type passed to them except for the equality and inequality operators (<, <=, >, >=, ==, !=) which return bool.

<table>
<tr><th></th><th>+</th><th>-</th><th>*</th><th>/</th><th>& (bitwise and)</th><th>| (bitwise or)</th><th>&& (logical and)</th><th>|| (logical or)</th><th><</th><th><=</th><th>></th><th>>=</th><th>==</th><th>!=</th><th>!</th></tr>
<tr><td>int</td><td>X *</td><td>X *</td><td>X *</td><td>X *</td><td>X</td><td>X</td><td></td><td></td><td>X *</td><td>X *</td><td>X *</td><td>X *</td><td>X *</td><td>X *</td><td></td></tr>
</table>

float	X *	X *	X *	X *					X *	X *	X *	X *	X *	X *	
char													X	X	
bool							X	X					X	X	X
func													X	X	
array	X (concatenation)												X	X	

* If one argument is a float and the other is an int, the int will be promoted to a float.

Type System
Variables are statically typed. Once a variable is assigned a type, it can not be changed.

Typecasting
Int can be implicitly cast to floats when assigning to variables or passing to operators or functions. No other automatic typecasting or promotion is done.

Anything can be converted to a string using the built in string() function.

Binding
Cb is statically bound. The compiler figures out what all identifiers mean at compile time.

Variable Creation and Use
Variables don't need to declared before use, but can be. This is only recommended for cases where the type can't be determined automatically. They can't be used until assigned to. Assignment is done with '='. An assignment statement can have one or more values per side although the same number must be on each side. If more than one is given, they are comma separated.

There are no global or static variables.

Functions
Functions are called using the () syntax. A function may be called by name, or a func variable may be called.

```
add_one(int i):
    return i + 1

int main():
    add_one(5)
    f = add_one
    f(4)
    return 0
```

Functions take 0 or more arguments and return 0 or more values.

```
foo(int a):
    ...
```

or

```
int, char bar():
    return 5, 'a'
```

Arguments are passed with copy semantics.

There is no function overloading.

Functions must be declared before being used. Recursion is allowed.

Functions can only be declared at the top level of the source code. Ie, not within other functions.

Exceptions
Functions can throw exceptions which causes cascading "returns" of the exception until a catch is found. Exceptions are ints. If an exception is not caught, the program terminates. If an exception is caught, the int thrown is assigned to the variable specified in the catch statement.

```
foo(int x):
    try:
        bar(x)
        return 0
    catch e:
       return 1

bar(int x):
    throw 1
```

Namespace
There is one namespace for all functions, variables, and types.

I/O
Done with
out(char c), err(char c)
and
char in()

Milestones
1. Grammar for all v 1 features.
2. Automated test framework (grab from last PLT project).
3. Variables with simple types. Operators.
4. I/O.
5. Function declaration and calling.
6. func type. Calling functions via func variables.
7. Exceptions.
8. The initial implementation will not include arrays or strings. If time permits (hah), I will add them later.

Arrays (v 2)
Array elements are accessed with []. Arrays keep track of their size and accesses are bounds checked.
Arrays are reference counted.

What do they contain?
memory management
declaration
manipulation

Strings (v 2)
The string type is syntactic sugar for arrays of chars.

Implicit casting to string?

Nicolas Viennot

COMS W4115 – Project Proposal

ltc

less than C

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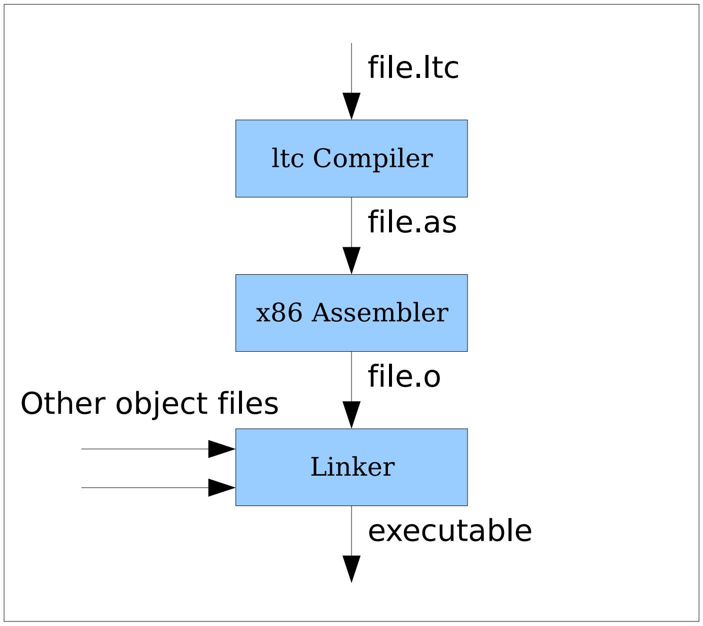
Introduction

The ltc is a very small subset of the C language. The project consists of creating a compiler written in ocaml that translate ltc code into assembly.

Overview

The standard GNU tools `as` and `ld` are used as assembler and linker.



Language features

The ltc syntax is quite similar to C: statements end with “;”, blocks are surrounded with “{ }”. the language has very limited features: arrays and pointers are not supported and there are no variable types (only integer). The major differences between ltc and C are described as follows:

Variables

- variables can only be 32 bits signed integers
- variables don't need to be declared
- global/static variables are not allowed
- variables are accessible in the function scope

Operators

- only the aritmetic, comparison, bitwise and assignment operators are available
- operator precedence is the same as in C.

Functions

- functions can be recursive
- arguments are passed by value
- functions always return an integer and the return value is implicitly given by the result of the last statement
- inline functions are not available

Control

- the do..while construction is not available
- the switch keyword is not available
- labels, goto, if/else, while and for loops, behave like C

Comments

- /* this is a comment */, they can be nested
- // this is also a comment

External calls

External functions can be called by including the right .o object files while linking. No “extern” declaration is needed, the linker will complain if the function doesn't exist.
To communicate with the external world, two functions are provided in the “library”: `input()` and `output()`.

Generated Assembly

The generated assembly is not optimized at all. Temporary values are stored on the stack (not in registers), like every other variables which is very inefficient.

Code sample

```
pow(a, b)
{
      if (b == 0)
            1; /* no return keyword */
      else
            a * pow(a, b-1);  /* recursion */
}

main()
{
      a = b = input();  /* read from stdin */

      b += 2;

      for (i = 1; i <= 5; i++) {
            c = pow(a, i);
            output(2 * (c + b)); /* print to stdout */
      }

      1;
}
```

Appendix B - LRM

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COMS W4115 - C Flat Reference Manual

1 Introduction

The C Flat language is mostly a subset of the C language. Some of the core functionalities of C has been stripped: there is no preprocessor, no structs, no strings, not even pointers. it's goal is purely educational. Originally Nico and Dan were working on two separate languages. The two projects merged, taking some features from each, and this is the resulting language. This document is inspired by the C Reference Manuel by Dennis Ritchie.

2 Lexical conventions

2.1 Whitespace

A tab, a space or a new line is a whitespace. At least one of these charaters is required to separate adjacent identifiers, constants, and certain oparator-pairs.

2.2 Comments

There are two ways to place comments: `//` introduces a comment which ends with a end of line. `/*` also introduces a comment which ends with `*/`, they can be nested. A `//` inside a `/* */` comment is ignored.

2.3 Identifiers

An identifier is a sequence of letters and digits. The first charater must be alphabetic. The underscore counts as alphabetic. An identifier is case sensitive.

2.4 Keywords

The following identifiers are reserved for use as keywords, and may not be used otherwise:
`return break continue if else for while try catch throw`

2.5 Constants

There is only one kind of constant: a 32 bits signed integer. Such a constant is a sequence of digits represented in its decimal form.

3 Expressions

An expression evaluates to a 32 bits signed integer. The precedence of operators is described in the syntax summary.

3.1 identifier

An identifier evaluates to the value of the corresponding variable.

3.2 literal

A decimal number is an expression.

3.3 (expression)

A parenthesized expression evaluates to the parenthesized expression.

3.4 identifier (expression-list$_{\text{opt}}$)

A function call is an expression. The arguments are optional and separated with a comma. They are evaluated from left to right before the call (applicative order). The value returned by the function is the value the callee returns with a `return` statement.

3.5 -expression

The result is the negative of the expression.

3.6 +expression

The result is the expression itself.

3.7 !expression

The result of the logical negation operator `!` is 1 if the value of the expression is 0, 0 if the value of the expression is non-zero.

3.8 ~expression

The ~ operator yields the one's complement of its operand.

3.9 identifier++

The referred variable is incremented when evaluated. The expression evalutaes to the value of the variable before the increment.
Note that the statement "`{a = 0; b = 0; b = a++ + a++; }`" sets the value of `a` to 2, and `b` to 1.

3.10 identifier--

The referred variable is decremented when evaluated. The expression evaluates to the value of the variable before the decrement.

3.11 ++identifier

The referred variable is incremented when evaluated. The expression evaluates to the value of the variable after the increment.

3.12 --identifier

The referred variable is decremented when evaluated. The expression evaluates to the value of the variable after the decrement.

3.13 expression * expression

The binary `*` operator indicates multiplication.

3.14 expression / expression

The binary `/`operator indicates division.

3.15 expression `%` expression

The binary `%` operator yields the remainder from the division of the first expression by the second. The remainder has the same sign as the dividend.

3.16 expression `+` expression

The result is the sum of the expressions.

3.17 expression `-` expression

The result is the difference of the expressions.

3.18 expression `>>` expression
expression `<<` expression

The value of the right hand side operand should be non-negative and less than 32, if not the result is undefined.
The value of "E1 `>>` E2" is E1 arithmetically right-shifted by E2 bit positions. Vacated bits are filled by a copy of the sign bit of the first expression.
The value of "E1 `<<` E2" is R1 left-shifted by E2 bit positions. Vacated bits are 0-filled.

3.19 expression `<` expression
expression `>` expression
expression `<=` expression
expression `>=` expression

The operators `<` (less than), `>` (greater than), `<=` (less than or equal to), `>=` (greater than or equal to) all yield 0 if the specified relation is false and 1 if it is true.

3.20 expression `==` expression
expression `!=` expression

The operators `==` (equal to) and the `!=` (not equal to) yield 0 if the specified relation is false, 1 if it is true.

3.21 expression `&` expression

The `&` operator yield the bitwise `and` function of the operands.

3.22 expression ˆ expression

The `&` operator yield the bitwise exclusive `or` function of the operands.

3.23 expression `|` expression

The `|` operator yield the bitwise inclusive `or` function of the operands.

3.24 expression `&&` expression

The `&&` operator returns 1 if both operands are non-zero, 0 otherwise. Both operands are always evaluated.

3.25 expression `||` expression

The `||` operator returns 1 if either of its operands is non-zero, 0 otherwise. Both operands are always evaluated.

3.26 identifier `=` expression

The value of the referred variable is replaced by the value of the expression.

3.27 identifier `+=` expression
identifier `-=` expression
identifier `*=` expression
identifier `/=` expression
identifier `%=` expression
identifier `>>=` expression
identifier `<<=` expression
identifier `&=` expression
identifier `^=` expression
identifier `|=` expression

An expression of the form “id op= expr” is equivalent to “id = id op expr”.

4 Statements

Statements are executed in sequence.

4.1 Expression statement

Most statement are expression statements, which have the form
  expression `;`

4.2 Compound statement

So that several statements can be used where one is expected, the compound statement is provided:

compound-statement:

  `{` statement-list$_{\text{opt}}$ `}`

statement-list:

  statement
  statement statement-list

4.3 Conditional statement

The two forms of the conditional statement are

`if (` expression `)` statement

`if (` expression `)` statement `else` statement

In both cases the expression is evaluated and if it is non-zero, the first substatement is executed. In the second case the second substatement is executed if the expression is 0. As usual the “else” ambiguity is resolved by connecting an `else` with the last encountered elseless `if`.

4.4 While statement

The `while` statement has the form

`while (` expression `)` statement

The substatement is executed repeatedly so long as the value of the expression remains non-zero. The test takes place before each execution of the statement.

4.5 For statement

The `for` statement has the form

`for (` expression-1$_{\text{opt}}$ `;` expression-2$_{\text{opt}}$ `;` expression-3$_{\text{opt}}$ `)` statement

This statement is equivalent to

```
expression-1;
while ( expression-2 ) {
    statement
    expression-3;
}
```

Any or all the expression may be dropped. A missing expression-2 makes the implied `while` clause equivalent to “while(1)”. Other missing expressions are simply dropped from the expansion above.

4.6 Break statement

The statement

`break;`

casuses termination of the smallest enclosing `while` or `for` statement; control passes to the statement following the terminated statement.

4.7 Continue statement

The statement

`continue;`

causes control to pass to the loop-continuation portion of the smallest enclosing `while` or `for` statement; that is to the end of the loop. In case of a `for` loop of the form “`for(e1;e2;e3) {...}`”, `e3` is evaluated before checking `e2`.

4.8 Return statement

A function returns to its caller by means of the `return` statement

`return` expression `;`

The value of the expression is returned to the caller of the function.

4.9 Null statement

The null statement has the form

`;`

A null statement is useful to supply a null body to a looping statement such as `while`.

4.10 Try-catch statement

The two form of the try-catch statement are

`try` `{` statement-list$_{opt}$ `}catch` `(` identifier `)` `{` statement-list$_{opt}$ `}`

`try` `{` statement-list$_{opt}$ `}catch` `{` statement-list$_{opt}$ `}`

The statments enclosed in the try block are executed until an exception is thrown. In case no exception is thrown, the statments enclosed in the catch block are not executed. The first form of the try-catch statement allows to assign the value of the exception to a variable. Try-catch statement dynamically nest across function calls.

4.11 Throw statement

The throw statement has the form

`throw` expression `;`

Throwing an exception causes control to pass to the catch block of the nearest dynamically-enclosing try-catch statement. If none is found, it causes the program to terminate with an error. The given expression is the value of the thrown exception.

5 Program definition

A ltc program consists of a sequence of function definition.

program:

function-definition
function-definition program

function-definition:

identifier `(` parameter-list$_{opt}$ `)` `{` statement-list$_{opt}$ `}`

parameter-list:

identifier
identifier `,` parameter-list

the same identifier cannot be used more than once in the parameter list. Within the same program, A function cannot be defined twice (name wise).
All functions return a integer value. A function can return to the caller without an explicit `return` statement, in this case the return value is undefined.

A simple example of a complete function definition:

```
max (a, b, c) {
  if (a > b) m = a; else m = b;
  if (m > c) return m; else return c;
}
```

6 Scope rules

There are no global variables, but only local variables which are statically binded. The scope of a local variable is the whole function where the variable is used. The scope of function parameters is the whole function.

Function scope is the entire program.

7 Declarations

Variables don't need to be declared, they are initialized to 0.
A function call can be made whether or not the function actually exists, the program will simply not link if a call to a non-existing function is made.

8 Namespace

Variables and function use different namespaces. Therefore such a function is correct: "`f() {f=1; return f; }`".

9 Syntax Summary

9.1 Expressions

expression:

identifier
literal
`(` expression `)`
identifier `(` expression-list$_{opt}$ `)`
`-`expression
`+`expression
`!`expression
$\sim$expression
`++`identifier
`--`identifier
identifier`++`
identifier`--`
expression binop expression
identifier asgnop expression

expression-list:

expression
expression `,` expression-list

The unary operators `- + !` $\sim$ have higher priority than binary operator.
Binary operators all group left to right and have priority decreasing as indicated:

binop:

`* / %`

```
+ -
>> <<
< > <= >=
== !=
&
∧
|
&&
||
```

Assignment operator all have the same priority, and all group right to left.

asgnop:

```
= += -= *= /= %= >>= <<= &= ∧= |=
```

9.2 Statements

statement:

expression ;

{ statement-list$_{\text{opt}}$ }

`if` (expression) statement

`if` (expression) statement `else` statement

`while` (expression) statement

`for` (expression$_{\text{opt}}$; expression$_{\text{opt}}$; expression$_{\text{opt}}$) statement

`break;`

`continue;`

`return` expression;

`try` { statement-list$_{\text{opt}}$ }`catch` { statement-list$_{\text{opt}}$ }

`try` { statement-list$_{\text{opt}}$ }`catch` (identifier) { statement-list$_{\text{opt}}$ }

`throw` expression;

;

statement-list:

statement

statement statement-list

9.3 Program definition

program:

function-definition
function-definition program

function-definition:

identifier `(` parameter-list$_{\text{opt}}$ `)` `{` statement-list$_{\text{opt}}$ `}`

parameter-list:

identifier
identifier `,` parameter-list

Appendix C - source

Makefile

```
OBJS = parser.cmo scanner.cmo backend.cmo sast.cmo cflat.cmo

CFLAGS="-m32"

cflat : $(OBJS) lib.o
	ocamlc -o cflat $(OBJS)

.PHONY: test
test : cflat tester.py test-cflat.txt
	./tester.py test-cflat.txt

scanner.ml : scanner.mll
	ocamllex scanner.mll

parser.ml parser.mli : parser.mly
	ocamlyacc parser.mly

%.cmo : %.ml
	ocamlc -c $<

%.cmi : %.mli
	ocamlc -c $<

.PHONY : clean
clean :
	rm -f cflat parser.ml parser.mli scanner.ml testall.log *.cmo *.cmi *.o
*.s test

# Generated by ocamldep *.ml *.mli
backend.cmo: ast.cmi
backend.cmx: ast.cmi
cflat.cmo: scanner.cmo sast.cmo parser.cmi backend.cmo
cflat.cmx: scanner.cmx sast.cmx parser.cmx backend.cmx
parser.cmo: ast.cmi parser.cmi
parser.cmx: ast.cmi parser.cmi
sast.cmo: ast.cmi
sast.cmx: ast.cmi
scanner.cmo: parser.cmi
scanner.cmx: parser.cmx
parser.cmi: ast.cmi
```

scanner.mll

```
{ open Parser }


let newline    = '\n' | "\r\n"
let whitespace = [' ' '\t'] | newline
let digit      = ['0'-'9']
let integer    = digit+
let alpha      = ['_' 'a'-'z' 'A'-'Z']
let alphanum   = alpha | digit
let identifier = alpha alphanum*

rule token = parse
    whitespace          { token lexbuf }
  | "//"                { comment_double_slash lexbuf }
  | "/*"                { comment_slash_star 0 lexbuf }

  (* arithmetic operators *)
  | "++"                { INC }
  | "--"                { DEC }
  | "-="                { MINUS_ASSIGN }
  | "+="                { PLUS_ASSIGN }
  | "*="                { TIMES_ASSIGN }
  | "/="                { DIVIDE_ASSIGN }
  | "%="                { MODULO_ASSIGN }
  | '-'                 { MINUS }
  | '+'                 { PLUS }
  | '*'                 { TIMES }
  | '/'                 { DIVIDE }
  | '%'                 { MODULO }

  (* must be before the "|" and "&" *)
  | "&&"                { AND }
  | "||"                { OR }

  (* bitwise operators *)
  | "<<="               { LSHIFT_ASSIGN }
  | ">>="               { RSHIFT_ASSIGN }
  | "&="                { BW_AND_ASSIGN }
  | "|="                { BW_OR_ASSIGN }
  | "^="                { BW_XOR_ASSIGN }
  | "<<"                { LSHIFT }
  | ">>"                { RSHIFT }
  | "~"                 { BW_NOT }
  | "&"                 { BW_AND }
  | "|"                 { BW_OR }
  | "^"                 { BW_XOR }

  (* logic operators *)
  (* done before
  | "&&"                { AND }
  | "||"                { OR }
  *)
  | "<="                { LEQ }
  | ">="                { GEQ }
  | "!="                { NEQ }
```

```
  | "=="                 { EQ }
  | "!"                  { NOT }
  | '<'                  { LT }
  | '>'                  { GT }

  (* punctuation *)
  | '='                  { ASSIGN }
  | '('                  { LPAREN }
  | ')'                  { RPAREN }
  | '{'                  { LBRACE }
  | '}'                  { RBRACE }
  | ';'                  { SEMI }
  | ','                  { COMMA }

  (* keywords *)
  | "for"                { FOR }
  | "while"              { WHILE }
  | "if"                 { IF }
  | "else"               { ELSE }
  | "return"             { RETURN }
  | "break"              { BREAK }
  | "continue"           { CONTINUE }
  | "try"                { TRY }
  | "catch"              { CATCH }
  | "throw"              { THROW }
  | integer as lit       { LITERAL(int_of_string lit) }
  | identifier as id     { ID(id) }

  | eof                  { EOF }
  | _ as char            { raise (Failure("illegal character " ^ Char.escaped
char)) }

and comment_slash_star level = parse
    "*/"                 { if level = 0 then token lexbuf
                           else comment_slash_star (level-1) lexbuf }
  | "/*"                 { comment_slash_star (level+1) lexbuf }
  | eof                  { raise (Failure("Comment not closed")) }
  | _                    { comment_slash_star level lexbuf }

and comment_double_slash = parse
    newline              { token lexbuf }
  | _                    { comment_double_slash lexbuf}
```

parser.mly

```
%{ open Ast %}

%token INC DEC MINUS_ASSIGN PLUS_ASSIGN TIMES_ASSIGN DIVIDE_ASSIGN MODULO_ASSIGN
%token MINUS PLUS TIMES DIVIDE MODULO
%token LSHIFT_ASSIGN RSHIFT_ASSIGN BW_AND_ASSIGN BW_OR_ASSIGN BW_XOR_ASSIGN
%token LSHIFT RSHIFT BW_NOT BW_AND BW_OR BW_XOR
%token LEQ GEQ NEQ EQ NOT AND OR LT GT
%token ASSIGN LPAREN RPAREN LBRACE RBRACE SEMI COMMA
%token FOR WHILE IF ELSE RETURN BREAK CONTINUE TRY CATCH THROW
%token <int> LITERAL
%token <string> ID
%token EOF

%nonassoc NOELSE
%nonassoc ELSE

%right BW_AND_ASSIGN BW_XOR_ASSIGN BW_OR_ASSIGN LSHIFT_ASSIGN RSHIFT_ASSIGN
       TIMES_ASSIGN DIVIDE_ASSIGN MODULO_ASSIGN PLUS_ASSIGN MINUS_ASSIGN ASSIGN
%left OR
%left AND
%left BW_OR
%left BW_XOR
%left BW_AND
%left EQ NEQ
%left GT GEQ LT LEQ
%left LSHIFT RSHIFT
%left PLUS MINUS
%left TIMES DIVIDE MODULO
%nonassoc NOT BW_NOT U_PLUS U_MINUS

%start program
%type <Ast.program> program

%%

program:
   /* nothing */ { [] }
 | program fdecl { $2 :: $1 }

fdecl:
   ID LPAREN formals_opt RPAREN LBRACE stmt_list RBRACE
     { { _fname = $1;
         _formals = $3;
         _body = List.rev $6 } }

formals_opt:
    /* nothing */ { [] }
  | formal_list   { List.rev $1 }

formal_list:
    ID                   { [$1] }
  | formal_list COMMA ID { $3 :: $1 }

stmt_list:
    /* nothing */  { [] }
```

```
  | stmt_list stmt { $2 :: $1 }

stmt:
    expr SEMI { Expr($1) }
  | SEMI { Expr(Noexpr) }
  | RETURN expr SEMI { Return($2) }
  | LBRACE stmt_list RBRACE { Block(List.rev $2) }
  | IF LPAREN expr RPAREN stmt %prec NOELSE { If($3, $5, Block([])) }
  | IF LPAREN expr RPAREN stmt ELSE stmt    { If($3, $5, $7) }
  | FOR LPAREN expr_opt SEMI expr_opt SEMI expr_opt RPAREN stmt
     { For($3, $5, $7, $9) }
  | WHILE LPAREN expr RPAREN stmt { While($3, $5) }
  | BREAK SEMI { Break }
  | CONTINUE SEMI { Continue }
  | TRY LBRACE stmt_list RBRACE CATCH LBRACE stmt_list RBRACE
    { Try_catch(Block(List.rev $3), "", Block(List.rev $7)) }
  | TRY LBRACE stmt_list RBRACE CATCH LPAREN ID RPAREN LBRACE stmt_list RBRACE
    { Try_catch(Block(List.rev $3), $7, Block(List.rev $10)) }
  | THROW expr SEMI { Throw($2) }

expr_opt:
    /* nothing */ { Noexpr }
  | expr          { $1 }

expr:
    LITERAL          { Literal($1) }
  | ID               { Id($1) }

  | expr OR       expr { Binop($1, Or,      $3) }
  | expr AND      expr { Binop($1, And,     $3) }
  | expr BW_OR    expr { Binop($1, Bw_or,   $3) }
  | expr BW_AND   expr { Binop($1, Bw_and,  $3) }
  | expr BW_XOR   expr { Binop($1, Bw_xor,  $3) }
  | expr LSHIFT   expr { Binop($1, Lshift,  $3) }
  | expr RSHIFT   expr { Binop($1, Rshift,  $3) }
  | expr PLUS     expr { Binop($1, Add,     $3) }
  | expr MINUS    expr { Binop($1, Sub,     $3) }
  | expr TIMES    expr { Binop($1, Mult,    $3) }
  | expr DIVIDE   expr { Binop($1, Div,     $3) }
  | expr MODULO   expr { Binop($1, Modulo,  $3) }
  | expr EQ       expr { Binop($1, Equal,   $3) }
  | expr NEQ      expr { Binop($1, Neq,     $3) }
  | expr LT       expr { Binop($1, Less,    $3) }
  | expr LEQ      expr { Binop($1, Leq,     $3) }
  | expr GT       expr { Binop($1, Greater, $3) }
  | expr GEQ      expr { Binop($1, Geq,     $3) }

  | NOT    expr { Unop(Not,      $2) }
  | BW_NOT expr { Unop(Bw_not,   $2) }
  | PLUS   expr %prec U_PLUS   { Unop(Plus,     $2) }
  | MINUS  expr %prec U_MINUS  { Unop(Minus,    $2) }
  | INC    ID   { Incop(Pre_inc,  $2) }
  | DEC    ID   { Incop(Pre_dec,  $2) }
  | ID     INC  { Incop(Post_inc, $1) }
  | ID     DEC  { Incop(Post_dec, $1) }

  | ID BW_AND_ASSIGN expr { Assignop($1, Bw_and_assign, $3) }
  | ID BW_OR_ASSIGN  expr { Assignop($1, Bw_or_assign,  $3) }
```

```
  | ID BW_XOR_ASSIGN expr { Assignop($1, Bw_xor_assign, $3) }
  | ID LSHIFT_ASSIGN expr { Assignop($1, Lshift_assign, $3) }
  | ID RSHIFT_ASSIGN expr { Assignop($1, Rshift_assign, $3) }
  | ID TIMES_ASSIGN  expr { Assignop($1, Mult_assign,   $3) }
  | ID DIVIDE_ASSIGN expr { Assignop($1, Div_assign,    $3) }
  | ID MODULO_ASSIGN expr { Assignop($1, Modulo_assign, $3) }
  | ID PLUS_ASSIGN   expr { Assignop($1, Add_assign,    $3) }
  | ID MINUS_ASSIGN  expr { Assignop($1, Sub_assign,    $3) }
  | ID ASSIGN expr        { Assignop($1, Assign,        $3) }

  | ID LPAREN actuals_opt RPAREN { Call($1, $3) }
  | LPAREN expr RPAREN { $2 }

actuals_opt:
    /* nothing */ { [] }
  | actuals_list  { List.rev $1 }

actuals_list:
    expr                    { [$1] }
  | actuals_list COMMA expr { $3 :: $1 }
```

ast.mli

```ocaml
type binop =
    Add | Sub | Mult | Div | Modulo
  | Or | And | Bw_or | Bw_and | Bw_xor | Lshift | Rshift
  | Equal | Neq | Less | Leq | Greater | Geq

type assignop =
    Assign | Add_assign | Sub_assign | Mult_assign | Div_assign | Modulo_assign
  | Bw_or_assign | Bw_and_assign | Bw_xor_assign | Lshift_assign | Rshift_assign

type unop =
    Not | Bw_not | Plus | Minus

type incop =
    Pre_inc | Post_inc | Pre_dec | Post_dec

type expr =
    Literal  of int
  | Id       of string
  | Unop     of unop * expr
  | Incop    of incop * string
  | Binop    of expr * binop * expr
  | Assignop of string * assignop * expr
  | Call     of string * expr list
  | Noexpr

type stmt =
    Block     of stmt list
  | Expr      of expr
  | Return    of expr
  | If        of expr * stmt * stmt
  | For       of expr * expr * expr * stmt
  | While     of expr * stmt
  | Break
  | Continue
  | Try_catch of stmt * string * stmt
  | Throw     of expr

type func_decl = {
  _fname   : string;
  _formals : string list;
  _body    : stmt list;
}

type program = func_decl list

type func_decl_detail = {
  fname   : string;
  formals : string list;
  locals  : string list;
  body    : stmt list;
}

type program_detail = func_decl_detail list
```

sast.ml

```
open Ast
open Printf

type context = {
  in_loop   : bool;
  variables : string list ref;
}

(* returns l1 - l2 *)
let rec diff_list l1 = function
    [] -> l1
  | hd2 :: tl2 ->
    let rec diff_hd2 = function
        [] -> []
      | hd1 :: tl1 ->
          if hd1 = hd2 then diff_hd2 tl1
          else hd1 :: diff_hd2 tl1 in
    diff_list (diff_hd2 l1) tl2

(* add v to the context.variables list if not in the list *)
let add_variable context v =
  let rec add_unique_v = function
      [] -> [v]
    | hd :: tl ->
        if hd = v then hd :: tl
        else hd :: add_unique_v tl in
  context.variables := add_unique_v !(context.variables)

let rec check_expr fdecl context = function
    Literal(_)           -> ()
  | Id(v)                -> add_variable context v
  | Unop(_, e)           -> check_expr fdecl context e
  | Incop(_, v)          -> add_variable context v
  | Binop(e1, _, e2)     -> check_expr fdecl context e1;
                            check_expr fdecl context e2
  | Assignop(v, _, e)    -> add_variable context v;
                            check_expr fdecl context e
  | Call(_, el)          -> List.iter (check_expr fdecl context) el
  | Noexpr               -> ()

let rec check_stmt fdecl context = function
    Block(sl)            -> List.iter (check_stmt fdecl context) sl
  | Expr(e)              -> check_expr fdecl context e
  | Return(e)            -> check_expr fdecl context e
  | If(e, s1, s2)        -> check_expr fdecl context e;
                            check_stmt fdecl context s1;
                            check_stmt fdecl context s2
  | For(e1, e2, e3, s)   ->
      let context' = { context with in_loop = true } in
                            check_expr fdecl context' e1;
                            check_expr fdecl context' e2;
                            check_expr fdecl context' e3;
                            check_stmt fdecl context' s
  | While(e, s)          -> check_stmt fdecl context (For(Noexpr, e, Noexpr, s))
  | Break                -> if not context.in_loop then
```

```
                              raise (Failure("break keyword used outside a loop"))
  | Continue             -> if not context.in_loop then
                              raise (Failure("continue keyword used outside a
loop"))
  | Try_catch(s1, v, s2) -> check_stmt fdecl context s1;
                            add_variable context v;
                            check_stmt fdecl context s2
  | Throw(e)             -> check_expr fdecl context e

(* check a func_decl and returns a func_decl_detail *)
let check_func fdecl =
  (* first check that each formal is only declared once *)
  let rec check_formal_unique formal_list formal =
    (match formal_list with
        [] -> [formal]
      | hd :: tl ->
          if hd = formal then
             raise (Failure("formal " ^ formal ^ " is declared more than once" ^
                            " in function " ^ fdecl._fname))
          else
             hd :: check_formal_unique tl formal) in
  let _ = List.fold_left check_formal_unique [] fdecl._formals in

  let context = { in_loop = false; variables = ref [] } in
  check_stmt fdecl context (Block(fdecl._body));
  { fname = fdecl._fname;
    formals = fdecl._formals;
    locals = diff_list !(context.variables) fdecl._formals;
    body = fdecl._body }

(* check a program and returns a program_detail *)
let check_program funcs =
   (* first we check that a function is only declared once *)
    let rec check_funcs_unique fname_list fdecl =
      (match fname_list with
          [] -> [fdecl._fname]
        | hd :: tl ->
            if hd = fdecl._fname then
               raise (Failure("function " ^ fdecl._fname ^
                      " is declared more than once"))
            else
               hd :: check_funcs_unique tl fdecl) in
  let _ = List.fold_left check_funcs_unique [] funcs in

  List.map check_func funcs
```

backend.ml

```
open Ast
open Printf

type context = {
  label_count        : int ref;
  break_label        : string option;
  continue_label     : string option;
  return_label       : string option;
  function_try_level : int;
  loop_try_level     : int;
}

let get_new_label context =
  let l = !(context.label_count) in
  context.label_count := l + 1;
  ".L" ^ (string_of_int l)

let get = function
    Some(x) -> x
  | None -> ""

let rec index_of item n = function
    [] -> -1
  | hd::tl -> if hd = item then n else (index_of item (n+1) tl)

let id_to_offset fdecl id =
  let n = index_of id 0 fdecl.formals in
  if n >= 0 then
    4 * (n+2)
  else
    let n = index_of id 0 fdecl.locals in
    if n >= 0 then
      -4 * (n+1)
    else
      (* should never happen (SAST is doing its job) *)
      raise (Failure("undefined identifier " ^ id))

(*
an exception looks like this:
    struct exception {
      struct exception *next;
      void *catch_address;
      int  old_ebp;
    };
*)

let exception_context_size = 3*4

let stack_exception catch_label =
          "push ebp\n" ^
  sprintf "push offset %s\n" catch_label ^
          "push dword ptr [__exception_ptr]\n" ^
          "mov  [__exception_ptr], esp\n"

let unstack_exception n =
```

```
  sprintf "add  esp, %d\n" (exception_context_size * n)

let rec unwind_exception = function
    0 -> ""
  | n -> "mov eax, [__exception_ptr]\n" ^
         "mov eax, [eax]\n" ^
         "mov [__exception_ptr], eax\n" ^
         unwind_exception (n-1)

let rec eval_expr_to_eax fdecl = function
    Literal(l) ->
      sprintf "mov eax, %d\n" l

  | Id(s) ->
      sprintf "mov eax, [ebp+%d]\n" (id_to_offset fdecl s)

  | Unop(o, e) ->
      eval_expr_to_eax fdecl e ^
      (match o with
          Not      -> "test  eax, eax\n" ^
                      "setz  al\n" ^
                      "movzx eax, al\n"
        | Bw_not   -> "not   eax\n"
        | Plus     -> ""
        | Minus    -> "neg   eax\n")

  | Incop(o, v) ->
    let asm = function
        Pre_inc | Post_inc ->
          sprintf "inc dword ptr [ebp+%d]\n" (id_to_offset fdecl v)
      | Pre_dec | Post_dec->
          sprintf "dec dword ptr [ebp+%d]\n" (id_to_offset fdecl v) in
    (match o with
        Pre_inc  | Pre_dec  -> asm o ^ eval_expr_to_eax fdecl (Id(v))
      | Post_inc | Post_dec -> eval_expr_to_eax fdecl (Id(v)) ^ asm o)

  | Binop(e1, o, e2) ->
      eval_expr_to_eax fdecl e1 ^
      "push eax\n" ^
      eval_expr_to_eax fdecl e2 ^
      "pop  ecx\n" ^
      "xchg eax, ecx\n" ^
      (* eax contains e1, ecx contains e2 *)

      (match o with
          Equal | Neq | Less | Leq | Greater | Geq ->
            "cmp eax, ecx\n"
        | _ -> "") ^

      (match o with
          Add     -> "add   eax, ecx\n"
        | Sub     -> "sub   eax, ecx\n"
        | Mult    -> "imul  eax, ecx\n"
        | Div     -> "cdq\n" ^
                     "idiv  ecx\n"
        | Modulo  -> "cdq\n" ^
                     "idiv  ecx\n" ^
                     "mov   eax, edx\n"
```

```
      | Or      -> "or    eax, ecx\n" ^
                   "setnz al\n"
      | And     -> "test  eax, eax\n" ^
                   "setnz al\n" ^
                   "test  ecx, ecx\n" ^
                   "setnz cl\n" ^
                   "and   al, cl\n"
      | Bw_or   -> "or    eax, ecx\n"
      | Bw_and  -> "and   eax, ecx\n"
      | Bw_xor  -> "xor   eax, ecx\n"
      | Lshift  -> "sal   eax, cl\n"
      | Rshift  -> "sar   eax, cl\n"
      | Equal   -> "sete  al\n"
      | Neq     -> "setne al\n"
      | Less    -> "setl  al\n"
      | Leq     -> "setle al\n"
      | Greater -> "setg  al\n"
      | Geq     -> "setge al\n") ^

    (match o with
        Or | And | Equal | Neq | Less | Leq | Greater | Geq ->
          "movzx eax, al\n"
      | _ -> "")

| Assignop(v, o, e) ->
    let assign_binop binop =
      eval_expr_to_eax fdecl (Assignop(v, Assign, Binop(Id(v), binop, e))) in
    (match o with
        Assign         -> eval_expr_to_eax fdecl e ^
                          sprintf "mov [ebp+%d], eax\n" (id_to_offset fdecl v)
      | Add_assign     -> assign_binop Add
      | Sub_assign     -> assign_binop Sub
      | Mult_assign    -> assign_binop Mult
      | Div_assign     -> assign_binop Div
      | Modulo_assign  -> assign_binop Modulo
      | Bw_or_assign   -> assign_binop Bw_or
      | Bw_and_assign  -> assign_binop Bw_and
      | Bw_xor_assign  -> assign_binop Bw_xor
      | Lshift_assign  -> assign_binop Lshift
      | Rshift_assign  -> assign_binop Rshift)

| Call(f, el) ->
    let push_func_args =
      let prepare_arg e =
        eval_expr_to_eax fdecl e ^
        "push eax\n" in
      String.concat "" (List.map prepare_arg el) ^
      let swap_two_args i j =
        sprintf "mov  eax, [esp+%d]\n" (4 * i) ^
        sprintf "xchg eax, [esp+%d]\n" (4 * j) ^
        sprintf "mov  [esp+%d], eax\n" (4 * i) in
      let rec reverse_all_args i j =
          if i < j then
            swap_two_args i j ^
            reverse_all_args (i+1) (j-1)
          else "" in
      reverse_all_args 0 (List.length el - 1) in
    push_func_args ^
```

```
      sprintf "call %s\n" f ^
      sprintf "add  esp, %d\n" (4 * (List.length el))

  | Noexpr -> ""

let rec string_of_stmt context fdecl = function
    Block(stmts) ->
      String.concat "" (List.map (string_of_stmt context fdecl) stmts)

  | Expr(expr) -> eval_expr_to_eax fdecl expr

  | Return(expr) ->
      unwind_exception  context.function_try_level ^
      unstack_exception context.function_try_level ^
      eval_expr_to_eax fdecl expr ^
      sprintf "jmp %s\n" (get context.return_label)

  | If(e, s1, s2) ->
      let else_label    = get_new_label context
      and exit_if_label = get_new_label context in
      eval_expr_to_eax fdecl e ^
              "test eax, eax\n" ^
      sprintf "jz   %s\n" else_label ^
      string_of_stmt context fdecl s1 ^
      sprintf "jmp  %s\n" exit_if_label ^
      sprintf "%s:\n" else_label ^
      string_of_stmt context fdecl s2 ^
      sprintf "%s:\n" exit_if_label

  | For(e1, e2, e3, s) ->
      let loop_begin_label = get_new_label context
      and loop_label       = get_new_label context
      and loop_exit_label  = get_new_label context in
      let context' = { context with continue_label = Some loop_label;
                                    break_label    = Some loop_exit_label;
                                    loop_try_level = 0 } in
      eval_expr_to_eax fdecl e1 ^
      sprintf "jmp %s\n" loop_begin_label ^
      sprintf "%s:\n" loop_label ^
      eval_expr_to_eax fdecl e3 ^
      sprintf "%s:\n" loop_begin_label ^
      (match e2 with
          Noexpr -> ""
        | _ -> eval_expr_to_eax fdecl e2 ^
                         "test eax, eax\n" ^
               sprintf "jz   %s\n" loop_exit_label) ^
      string_of_stmt context' fdecl s ^
      sprintf "jmp %s\n" loop_label ^
      sprintf "%s:\n" loop_exit_label

  | While(e, s) ->
      string_of_stmt context fdecl (For(Noexpr, e, Noexpr, s))

  | Break ->
      unwind_exception  context.loop_try_level ^
      unstack_exception context.loop_try_level ^
      sprintf "jmp %s\n" (get context.break_label)
```

```
  | Continue ->
      unwind_exception  context.loop_try_level ^
      unstack_exception context.loop_try_level ^
      sprintf "jmp %s\n" (get context.continue_label)

  | Try_catch(s1, v, s2) ->
      let catch_label      = get_new_label context
      and exit_label       = get_new_label context in
      let context' = { context with
                         function_try_level = context.function_try_level + 1;
                         loop_try_level     = context.loop_try_level + 1} in
      stack_exception catch_label ^
      string_of_stmt context' fdecl s1 ^
      unwind_exception 1 ^
      unstack_exception 1 ^
      sprintf "jmp %s\n" exit_label ^
      sprintf "%s:\n" catch_label ^
      (match v with
          "" -> ""
        | _  -> sprintf "mov [ebp+%d], edx\n" (id_to_offset fdecl v)) ^
      string_of_stmt context fdecl s2 ^
      sprintf "%s:\n" exit_label

  | Throw(e) ->
      let caught_exception = get_new_label context in
      eval_expr_to_eax fdecl e ^
              "mov  edx, eax\n" ^
              "mov  ecx, [__exception_ptr]\n" ^
              "test ecx, ecx\n" ^
      sprintf "jnz  %s\n" caught_exception ^
              "push edx\n" ^
              "call __uncaught_exception\n" ^
      sprintf "%s:\n" caught_exception ^
      unwind_exception 1 ^
              "lea  esp, [ecx+12]\n" ^ (* exception is unstacked *)
              "mov  ebp, [ecx+8]\n" ^
              "jmp  [ecx+4]\n"

let string_of_fdecl context fdecl =
  let context' = { context with return_label = Some (get_new_label context) } in
  sprintf ".globl %s\n" fdecl.fname ^
  sprintf ".type %s, @function\n" fdecl.fname ^
  sprintf "%s:\n" fdecl.fname ^
          (* creating frame *)
          "push ebp\n" ^
          "mov  ebp, esp\n" ^
          (* instead of "sub esp, 4*num_locals", we "push 0" num_locals times,
             this way, the local variables are cleared on the fly *)
          "xor  eax, eax\n" ^
  String.concat "" (List.map (fun _ -> "push eax\n") fdecl.locals) ^
          "push ecx\n" ^
          "push edx\n" ^
  string_of_stmt context' fdecl (Block(fdecl.body)) ^
  sprintf "%s:\n" (get context'.return_label) ^
          "pop  edx\n" ^
          "pop  ecx\n" ^
          "mov  esp, ebp\n" ^
          "pop  ebp\n" ^
```

```
          "ret\n"

let generate_asm funcs =
  let context = { label_count        = ref 0;
                  continue_label     = None;
                  break_label        = None;
                  return_label       = None;
                  function_try_level = 0;
                  loop_try_level     = 0 } in
  ".intel_syntax noprefix\n" ^
  ".text\n" ^
  String.concat "" (List.map (string_of_fdecl context) funcs) ^
  ".ident \"C Flat compiler 0.1\"\n"
```

cflat.ml

```
let _ =
  try
    let lexbuf = Lexing.from_channel stdin in
    let program = Parser.program Scanner.token lexbuf in
    let program_detail = Sast.check_program program in
      print_string (Backend.generate_asm program_detail); exit 0
  with
      Failure(s)          -> prerr_endline ("Error: " ^ s); exit 1
    | Parsing.Parse_error -> prerr_endline ("Syntax error"); exit 1
```

lib.c

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

#define asmlinkage __attribute__((regparm(0)))

asmlinkage int in(void) {
  int i;
  scanf("%d", &i);
  return i;
}

asmlinkage void out(int val) {
  printf("%d\n", val);
}

asmlinkage void __uncaught_exception(int ex) {
  printf("uncaught exception: %d\n", ex);
  exit(1);
}

void *__exception_ptr;
```

tester.py

```python
#!/usr/bin/env python

import commands
import os
import sys
from popen2 import Popen4

def compile_and_run(compiler, code):
    """Returns (compile status, output).
    compile status is 'OK' or 'BAD'.
    If compile fails, output has compiler output. If compile succeeds, it has
    the output of the program run.

    """
    proc = Popen4(compiler)
    proc.tochild.write(code)
    proc.tochild.close()
    if proc.wait() != 0:
        return ('BAD', proc.fromchild.read())
    proc = Popen4('./test | xargs')
    return ('OK', proc.fromchild.read().strip())

def print_indented(message):
    for line in message.splitlines():
        print "     ", line

def run_test(compiler, code, correct_result):
    """Returns True if the test passes, otherwise False."""
    status, output = compile_and_run(compiler, code)
    if correct_result == 'BAD':
        if status == 'BAD':
            print "PASS"
            return True
        elif status == 'OK':
            print "FAIL: Bad code compiled. Code:"
            print_indented(code)
            return False
    elif correct_result == 'OK':
        if status == 'BAD':
            print "FAIL: Good code didn't compile. Code:"
            print_indented(code)
            print "Compiler output:"
            print_indented(output)
            return False
        elif status == 'OK':
            print "PASS"
            return True
    else:
        if status == 'BAD':
            print "FAIL: Good code didn't compile. Code:"
            print_indented(code)
            print "Compiler output:"
            print_indented(output)
            return False
        elif correct_result == output:
```

```python
            print "PASS"
            return True
        else:
            print "FAIL: Incorrect output from execution. Code:"
            print_indented(code)
            print "Executed code output:"
            print_indented(output)
            print "Correct output:"
            print_indented(correct_result)
            return False

if len(sys.argv) < 2:
    print "You must specify a test file."
    exit(1)
test_file_name = sys.argv[1]
test_file = open(test_file_name)
print "Loading test file '%s'." % test_file_name
compiler = '#'
while compiler.startswith('#'):
    compiler = test_file.readline().strip()
print "Using compile command '%s'." % compiler
test_count = 0
pass_count = 0
code = ""
for line in test_file:
    if line == "...\n":
        code = ""
    elif line.startswith("... "):
        test_count += 1
        correct_result = line.strip("\n")[4:]
        if (run_test(compiler, code, correct_result)):
            pass_count += 1
    else:
        code += line
test_file.close()
print "%d / %d tests passed." % (pass_count, test_count)
```

test-cflat.txt

```
# The first line that doesn't start with a '#' should be the compiler command.
# It should read source code from stdin and produce an executable named
# 'test'.
bash -c '(./cflat > test.s && gcc -m32 -c test.s -o test.o && gcc -m32 test.o
lib.o -o test)'

After the compiler command, anything not within a test case (surrounded by ...)
is ignored.
The closing ... should be followed by a space and then the desired result of the
test:
* OK if the code should compile,
* BAD if the code shouldn't compile, or
* Any other single line string which the code, when run, should produce.
  Whitespace may be trimmed from the front or back.


   *** Compiling ***
...
main() {
}
... OK

...
main() {
  bad
}
... BAD


   *** Comments ***
...
main() { }
/*
... BAD

...
main() {
  out(1);
  /* out(2); /* out(3); */ // */
  /* garbage */
  out(4); // out(5); garbage
  out(6);
}
... 1 4 6

   *** Variables ***
...
f(a, b) {
  out(a);
  out(b);
}
main() {
  out(a); /* a should be initialized to 0 */
  a = 1;
  b = a;
```

```
  out(b);
  out(a+b);
  f(2, 3);
}
... 0 1 2 2 3

...
/* variable can have the same name as a function */
f(f) {
  out(f);
}
main() {
  f = 2;
  f(f);
}
... 2

...
/* local variable discovery */
dummy(a) { }
a() { v; }
b() { !v; }
c() { v++; }
d() { v+0; }
e() { 0+v; }
f() { v+=0; }
g() { v=0; }
h() { dummy(v); }
i() { { v; } }
j() { return v; }
k() { if (v); }
l() { for(v;;); }
m() { for(;v;); }
n() { for(;;v); }
o() { while (v); }
p() { try {} catch(v) {} }
q() { throw v; }
main() { }
... OK


   *** Operators correctness ***
...
main() {
  /* Unop */
  out(-3);
  out(+ - + - + - + 4);
  out(!0);
  out(!2);
  out(!!2);
  out(~10);
  out(~~10);
}
... -3 -4 1 0 1 -11 10

...
main() {
  /* increment and decrement */
```

```
  out(a++);
  out(a);
  out(a--);
  out(a);
  out(++a);
  out(a);
  out(--a);
  out(a);
  out(a+++a++);
  out(a);
  out(a--+a--);
  out(a);
}
... 0 1 1 0 1 1 0 0 1 2 3 0

...
main() {
  /* Arithmetic binops */
  out(3+1);
  out(3+-1);
  out(-2+-2);
  out(3-1);
  out(3- -1);
  out(-1- -2);
  out(3*2);
  out(-2*3);
  out(-1*-1);
  out(12/4);
  out(6/-2);
  out(-5/-5);
  out(10%4);
  out(10%-4);
  out(-10%4);
  out(-10%-4);
}
... 4 2 -4 2 4 1 6 -6 1 3 -3 1 2 2 -2 -2

...
main() {
  /* Bitwise binops */
  out(3<<2);
  out(-1<<1);
  out(12>>2);
  out(-1>>1);
  out(1|4);
  out(3&5);
  out(3^5);
}
... 12 -2 3 -1 5 1 6

...
main() {
  /* Assign binops */
  a = 0; a += 2; out(a);
  a = 0; a -= 2; out(a);
  a = 2; a *= 3; out(a);
  a = 6; a /= 2; out(a);
  a = 7; a %= 4; out(a);
```

```
  a = 3; a <<= 2; out(a);
  a = 12; a >>= 2; out(a);
  a = 1; a |= 4; out(a);
  a = 3; a &= 5; out(a);
  a = 3; a ^= 5; out(a);
}
... 2 -2 6 3 3 12 3 5 1 6

...
main() {
  /* Logic binops */
  out(-2>-1);
  out(0>-1);
  out(0>0);
  out(1>0);

  out(-2>=-1);
  out(0>=-1);
  out(0>=0);
  out(1>=0);

  out(-1<-2);
  out(-2<0);
  out(1<1);
  out(0<1);

  out(-1<=-2);
  out(-2<=0);
  out(1<=1);
  out(0<=1);

  out(1==1);
  out(1==0);
  out(1!=1);
  out(1!=0);

  out(0&&1);
  out(1&&0);
  out(1&&3);
  out(0&&0);

  out(0||0);
  out(1||0);
  out(0||1);
  out(1||3);
}
... 0 1 0 1 0 1 1 1 0 1 0 1 0 1 1 1 1 0 0 1 0 0 1 0 0 1 1 1
```

*** Operator precedence ***

```
...
op(expr, wanted, not_wanted) {
  out((expr == wanted) && (wanted != not_wanted));
}
main() {
   /* left assoc test */
  out(2) * out(3) * out(4);
```

```
  /* precedence test */
  op(~2*3,    (~2)*3,    ~(2*3));
  op(1+2*3,   1+(2*3),   (1+2)*3);
  op(1<<2+3,  1<<(2+3),  (1<<2)+3);
  op(1<2+3,   1<(2+3),   (1<2)+3);
  op(1==2<1,  1==(2<1),  (1==2)<1);
  op(2&2==2,  2&(2==2),  (2&2)==2);
  op(1^2&3,   1^(2&2),   (1^2)&2);
  op(3|2^3,   3|(2^2),   (3|2)^2);
  op(0&&2|1,  0&&(2|1),  (0&&2)|1);
  op(1||2&&0, 1||(2&&0), (1||2)&&0);

  /* right assoc test */
  a = 1; b = 2; c = 3;
  a = b = c;
  out(a); out(b); out(c);
}
... 2 3 4 1 1 1 1 1 1 1 1 1 1 3 3 3


   *** Function test ***
...
/* should compile, number of argument are not checked */
f(a,b,c) { }
main() { f(a); }
... OK

...
/* duplicate function */
f() {}
f() {}
main() {}
... BAD

...
/* duplicate formals */
f(a,b,a) {}
main() {}
... BAD

...
/* Function call evaluation order */
f(a, b, c) { out(a); out(b); out(c); }
g(a, b, c) { }
main() {
  f(1, 2, 3);
  g(out(4), out(5), out(6));
}
... 1 2 3 4 5 6

...
/* Recursive call test */
fib(x) {
        if (x < 3) return 1;
        return fib(x-1) + fib(x-2);
}
main() {
```

```
        out(fib(10));
}
... 55

...
main() {
  f(); /* will fail at linking stage */
}
... BAD
```

*** **if/else** ***

```
...
main() {
  if (1) out(1);
  else   out(2);

  if (0) out(3);
  else   out(4);

  if (0)      out(5);
  else if (1) out(6);
  else        out(7);

  if (1)
    if (0)      out(8);
    else        out(9);
  else        out(10);

  if (1)    out(11);
  if (0)    out(12);
  else      out(13);
}
... 1 4 6 9 11 13
```

*** Simple loop test ***

```
...
main() {
  sum = 0;
  for (i = 0; i <= 10; i++)
    sum += i;
  out(sum);
}
... 55

...
func(a) {
  return a-1;
}
main() {
  a = 10;
  while(func(a))
    a = func(a);
  out(a);
}
... 1
```

```
...
/* empty condition */
main() {
  for (;;) break;
  for (;;i++) {
    if (i == 3)
      break;
    out(i);
  }
}
... 0 1 2

...
main() {
  while () { }
}
... BAD

   *** Nested for/while ***
...
main() {
  for (i = 0; i < 2; i++) {
    while (0) { }
    for (j = 0; j < 2; j++)
      out (i + j);
  }
}
... 0 1 1 2


   *** break/continue tests ***
...
main() {
  if (1) {
    break;
  }
}
... BAD

...
main() {
  continue;
}
... BAD

...
/* multi level break/continue */
main() {
  for (i = 0; i < 5; i++) {
    for (j = 0; j < 5; j++) {
      if (j == 1)
        continue;
      else if (j == 3)
        break;
      out(i);
      out(j);
    }
    if (i == 2)
```

```
      break;
  }
}
... 0 0 0 2 1 0 1 2 2 0 2 2
```

*** Exceptions ***

```
...
/* nested try/catch across functions */
g() {
  throw 4;
}
f() {
  try {
    g();
  } catch (b) {
    out(b);
    throw b-1;
  }
}
main() {
  out(1);
  try {
    f();
    out(2);
  } catch (a) {
    out(a);
  }
  out(5);
}
... 1 4 3 5

...
/* exceptions in recursive functions caught outside */
f(x) {
  if (x == 0) {
    throw -1;
  } else {
    out(x);
    f(x-1);
  }
}
main() {
  try {
    f(3);
  } catch(e) {
    out(e);
  }
}
... 3 2 1 -1

...
/* exceptions in recursive functions caught inside */
f(x) {
  try {
    if (x == 0) {
      throw -1;
    } else {
```

```
      out(x);
      f(x-1);
    }
  } catch(e) {
    out(e);
  }
}
main() {
  f(3);
}
... 3 2 1 -1

...
/* continue/break in a loop */
main() {
  for (i=0; i < 5; i++) {
    try {
      try {
        if (i == 4)
          throw 2;
      } catch {
        break;
      }
      if (i == 2)
        continue;
    } catch { }
    out(i);
  }
  out(-1);
}
... 0 1 3 -1

...
/* return within a try */
f() {
  try {
    return 0;
  } catch {
  }
}

main() {
  try {
    f();
    throw 1;
  } catch (a) {
    out(a);
  }
  out(2);
}
... 1 2

...
/* not catching an exception */
main() {
  throw 1;
}
... uncaught exception: 1
```