CEC C Code Printer

Stephen A. Edwards
Columbia University
sedwards@cs.columbia.edu

Contents

1 The Printer Class

2 ⟨*printer class* 2⟩≡ (36b)

```
class Printer : public Visitor {
  typedef map<GRCNode *, int> CFGmap;
  typedef map<STNode *, int> STmap;
  CFGmap cfgmap;
  STmap stmap;

  vector<GRCNode*> nodes;
  CFGmap nodeNumber;
  map<GRCNode*, GRCNode*> ridom;

  map<GRCNode *, CStatement*> statementFor;

  static int nextLabel;
public:
  std::ostream &o;
  Module &m;
  GRCgraph *g;

  map<GRCNode *, string> labelFor;

  set<string> identifiers; // All C identifiers for avoiding name collisions
```

```
  // C identifiers for various objects

  typedef map<Counter *, string> CounterNames;
  CounterNames counterVar;

  typedef map<SignalSymbol *, string> SignalNames;
  SignalNames presenceVar;
  SignalNames valueVar;

  typedef map<STexcl *, string> StateNames;
  StateNames stateVar;

  typedef map<Sync *, string> TerminationNames;
  TerminationNames terminationVar;

  typedef map<VariableSymbol *, string> VariableNames;
  VariableNames variableVar;

  Printer(std::ostream &, Module &);
  virtual ~Printer() {}

  ⟨declarations 4a⟩
};
```

3a ⟨*definitions* 3a⟩≡ (36c) 3b▷

```
int Printer::nextLabel = 0;
```

3b ⟨*definitions* 3a⟩+≡ (36c) ◁3a 4b▷

```
Printer::Printer(std::ostream &o, Module &m) : o(o), m(m)
{
  g = dynamic_cast<AST::GRCgraph*>(m.body);
  if (!g) throw IR::Error("Module is not in GRC format");

  // Enumerate selection tree and CFG nodes
  g->enumerate(cfgmap, stmap);

  // Enter C reserved words into the identifiers list to avoid collisions

  // Note: float and double aren't in this list because they are equivalent
  // to Esterel's types of the same name

  char *keywords[] = {
    "int", "break", "char", "continue", "if", "else",
    "struct", "for", "auto", "do", "extern", "while", "register", "switch",
    "static", "case", "goto", "default", "return", "entry", "sizeof", NULL
  };

  for (char **k = keywords ; *k != NULL ; k++) identifiers.insert(*k);
}
```

2 Name Management

Return a unique identifier for the given name. Enters the name into the `identifiers` set to make sure its unique.

4a ⟨*declarations* 4a⟩≡ (2) 4c ▷

```
string uniqueID(string);
```

4b ⟨*definitions* 3a⟩+≡ (36c) ◁ 3b 6 ▷

```
string Printer::uniqueID(string name)
{
  string newname = name;

  char buf[10];
  int version = 1;

  while (contains(identifiers, newname)) {
    sprintf(buf, "%d", version++);
    newname = name + '_' + buf;
  }

  identifiers.insert(newname);
  return newname;
}
```

3 GRC Node printers

The main method here is `printExpr`, which writes a C *expression* for the given node to the output stream. This expression often has side effects, such as an assignment, but for conditional nodes, it returns the value of the node, which can be used as an argument in, say, an if-then-else statement.

4c ⟨*declarations* 4a⟩+≡ (2) ◁ 4a 4d ▷

```
void printExpr(ASTNode *n) { n->welcome(*this); }
```

3.1 Test and Action

These nodes contain expressions or statements that generate the real code.

4d ⟨*declarations* 4a⟩+≡ (2) ◁ 4c 4e ▷

```
Status visit(Test &t) { printExpr(t.predicate); return Status(); }
Status visit(Action &a) { printExpr(a.body); return Status(); }
```

3.2 Do-nothing nodes

These nodes are placeholders.

4e ⟨*declarations* 4a⟩+≡ (2) ◁ 4d 5a ▷

```
Status visit(EnterGRC&) { o << "1 /* EnterGRC */"; return Status(); }
Status visit(ExitGRC&) { o << "/* ExitGRC */"; return Status(); }
Status visit(STSuspend&) { o << "/* STSuspend */"; return Status(); }
```

3.3 Nop

You can hide arbitrary code in a string in a Nop node and have it emitted.

5a ⟨*declarations* 4a⟩+≡ (2) ◁4e 5b▷

```
Status visit(Nop& n) { o << n.body; return Status(); }
```

3.4 Switch

A switch node by itself returns an expression for its state variable.

5b ⟨*declarations* 4a⟩+≡ (2) ◁5a 5c▷

```
Status visit(Switch &s) {
  STexcl *e = dynamic_cast<STexcl*>(s.st);
  assert(e);
  assert(contains(stateVar, e));
  o << stateVar[e];
  return Status();
}
```

3.5 Enter

An enter node sets the value of its state depending on which child it is under. The visitor walks up the selection tree, starting at the selection tree node of the enter node, looking for the first exclusive node. The state value is simply the child number we came in on.

5c ⟨*declarations* 4a⟩+≡ (2) ◁5b 7a▷

```
Status visit(Enter &);
```

6 ⟨*definitions* 3a⟩+≡ (36c) ◁4b 7b▷

```
Status Printer::visit(Enter &e)
{
  STexcl *exclusive = 0;
  STNode *n = e.st;

  for (;;) {
    assert(n);

    STNode *parent = n->parent;

    // If we hit a parallel first, this Enter is unnecessary; do not generate
    // any code
    if (dynamic_cast<STpar*>(parent) != NULL) return Status();

    exclusive = dynamic_cast<STexcl*>(parent);
    if (exclusive != NULL) break; // found the exclusive node
    n = parent;
  }

  assert(exclusive != NULL);

  // Locate node n among the children of "parent"

  vector<STNode*>::iterator i = exclusive->children.begin();
  while (*i != n && i != exclusive->children.end()) i++;

  assert(i != exclusive->children.end());

  int childnum = i - exclusive->children.begin();

  assert(childnum >= 0);

  assert(contains(stateVar, exclusive));
  o << stateVar[exclusive] << " = " << childnum;

  return Status();
}
```

3.6 Terminate

These update the termination level of sync node. This uses a clever encoding that allows a bitwise AND operation to perform the maximum calculation.

level	encoding	binary
0	-1	1111
1	-2	1110
2	-4	1100
3	-8	1000

7a ⟨*declarations* 4a⟩+≡ (2) ◁5c 7c▷

```
Status visit(Terminate &);
```

7b ⟨*definitions* 3a⟩+≡ (36c) ◁6 8c▷

```
Status Printer::visit(Terminate &t)
{
  // If we have something other than a single data successor or it is not
  // a Sync, return nothing.
  if (t.dataSuccessors.size() != 1 || t.code == 0) {
    o << "/* Vacuous terminate */";
    return Status();
  }

  Sync *s = dynamic_cast<Sync*>(t.dataSuccessors.front());
  if (s == NULL) return Status();

  if ( contains(terminationVar, s) )
    o << terminationVar[s] << " &= -(1 << " << t.code << ")";
  return Status();
}
```

3.7 Sync

The sync node returns the value of its termination level. The encoding is a little unorthodox because of the trick used by Terminate nodes (see above):

level	result
0	0
1	1
2	3
3	7
4	15

7c ⟨*declarations* 4a⟩+≡ (2) ◁7a 8a▷

```
Status visit(Sync &s) {
  if ( contains(terminationVar, &s) )
    o << '~' << terminationVar[&s];
  return Status();
}
```

3.8 Fork

A fork node resets the termination level for its Sync node, if it has one.

8a ⟨*declarations* 4a⟩+≡ (2) ◁7c 8b▷

```
Status visit(Fork &f) {
  if (f.sync && contains(terminationVar, f.sync))
    o << terminationVar[f.sync] << " = -1";
  return Status();
}
```

4 Statement Printers

4.1 Emit and Exit

These both assign an optional value, if present, then set their respective presence variables.

FIXME: Emit must be fixed to work with ”combine” signals.

8b ⟨*declarations* 4a⟩+≡ (2) ◁8a 9b▷

```
Status visit(Emit &);
Status visit(Exit &);
```

8c ⟨*definitions* 3a⟩+≡ (36c) ◁7b 9a▷

```
Status Printer::visit(Emit &e)
{
  assert(e.signal);
  if (e.signal->type != NULL) {
    assert(contains(valueVar, e.signal));
    o << "(";
    if (e.value->type->name == "string") {
      o << "strcpy(" << valueVar[e.signal] << ", ";
      printExpr(e.value);
      o << ")";
    } else {
      o << valueVar[e.signal] << " = ";
      printExpr(e.value);
    }
    o << "), (";
  }
  assert(contains(presenceVar, e.signal));
  o << presenceVar[e.signal] << " = 1";
  if (e.signal->type) o << ")";
  return Status();
}
```

9a ⟨*definitions* 3a⟩+≡ (36c) ◁8c 10c▷

```
Status Printer::visit(Exit &e)
{
  assert(e.trap);
  if (e.trap->type) {
    assert(contains(valueVar, e.trap));
    o << valueVar[e.trap] << " = ";
    printExpr(e.value);
    o << ", ";
  }
  assert(contains(presenceVar, e.trap));
  o << presenceVar[e.trap] << " = 1";
  return Status();
}
```

4.2 DefineSignal

This resets the presence of a (local) signal.

9b ⟨*declarations* 4a⟩+≡ (2) ◁8b 10a▷

```
Status visit(DefineSignal &d)
{
  assert(contains(presenceVar, d.signal));
  o << presenceVar[d.signal] << " = 0";
  return Status();
}
```

4.3 Assign

10a ⟨*declarations* 4a⟩+≡ (2) ◁9b 10b▷

```
Status visit(Assign &a) {
  assert(a.variable->type);
  assert(contains(variableVar, a.variable));

  if (a.variable->type->name == "string") {
    // Use strcpy for strings
    o << "strcpy(" << variableVar[a.variable] << ", ";
    printExpr(a.value);
    o << ")";
  } else if ( dynamic_cast<BuiltinTypeSymbol*>(a.variable->type) ) {
    // Use assignment for other built-in types
    o << variableVar[a.variable] << " = ";
    printExpr(a.value);
  } else {
    // Call _<typename>(&lvalue, rvalue) for user-defined types
    o << '_' << a.variable->type->name
      << "(&" << variableVar[a.variable] << ", ";
    printExpr(a.value);
    o << ')';
  }
  return Status();
}
```

4.4 StartCounter

This assigns the initial count value to the given counter.

10b ⟨*declarations* 4a⟩+≡ (2) ◁10a 10d▷

```
Status visit(StartCounter &);
```

10c ⟨*definitions* 3a⟩+≡ (36c) ◁9a 11a▷

```
Status Printer::visit(StartCounter &s)
{
  assert(s.counter);
  assert(contains(counterVar, s.counter));
  o << counterVar[s.counter] << " = ";
  printExpr(s.count);
  return Status();
}
```

4.5 CheckCounter

This decrements the counter if its predicate is true and returns true if the counter has reached 0.

10d ⟨*declarations* 4a⟩+≡ (2) ◁10b 11b▷

```
Status visit(CheckCounter &);
```

11a ⟨*definitions* 3a⟩+≡ (36c) ◁10c 12c▷

```
Status Printer::visit(CheckCounter &s)
{
  assert(s.counter);
  assert(s.predicate);
  assert(contains(counterVar, s.counter));
  // FIXME: Is this safe?
  if (dynamic_cast<LoadVariableExpression*>(s.predicate)) {
    o << "0 == --" << counterVar[s.counter];
  } else {
    o << "0 == (";
    printExpr(s.predicate);
    o << " ? --" << counterVar[s.counter] << " : "
      << counterVar[s.counter] << ")";
  }
  return Status();
}
```

5 Expression Printers

5.1 LoadSignalExpression and LoadSignalValueExpression

11b ⟨*declarations* 4a⟩+≡ (2) ◁10d 12a▷

```
Status visit(LoadSignalExpression &e) {
  assert(contains(presenceVar, e.signal));
  o << presenceVar[e.signal];
  return Status();
}
```

This is straightforward unless the signal being read is a sensor. We are only allowed to read a sensor (by calling its input function, e.g., `MODULE_S_SENSOR()`) once a cycle. We use its presence variable to track whether the sensor has been read or not, for something like `?SENSOR`, generating

```
( SENSOR ? SENSOR_v : (SENSOR = 1, SENSOR_v = MODULE_S_SENSOR()) )
```

12a ⟨*declarations* 4a⟩+≡ (2) ◁11b 12b▷

```
Status visit(LoadSignalValueExpression &e) {
  assert(e.signal);
  assert(contains(valueVar, e.signal));
  assert(contains(presenceVar, e.signal));
  if (e.signal->kind == SignalSymbol::Sensor) {
    o << "( " << presenceVar[e.signal] << " ? " << valueVar[e.signal]
      << " : (" << presenceVar[e.signal] << " = 1,"
      << valueVar[e.signal] << " = "
      << m.symbol->name << "_S_" << e.signal->name << "()) )";
  } else {
    o << valueVar[e.signal];
  }
  return Status();
}
```

5.2 LoadVariableExpression

12b ⟨*declarations* 4a⟩+≡ (2) ◁12a 13b▷

```
Status visit(LoadVariableExpression &e) {
  assert(contains(variableVar, e.variable));
  o << variableVar[e.variable];
  return Status();
}
```

5.3 Unary and BinaryOp

12c ⟨*definitions* 3a⟩+≡ (36c) ◁11a 13a▷

```
Status Printer::visit(UnaryOp &op)
{
  o << '(';
  string s = op.op;
  if (s == "not") s = "!";
  o << s;
  assert(op.source);
  printExpr(op.source);
  o << ')';
  return Status();
}
```

13a ⟨*definitions* 3a⟩+≡ (36c) ◁12c 13d▷

```
Status Printer::visit(BinaryOp &op)
{
  o << '(';
  assert(op.source1);
  printExpr(op.source1);
  string s = op.op;
  if (s == "mod") s = "%";
  else if (s == "=") s = "==";
  else if (s == "<>") s = "!=";
  else if (s == "and") s = "&&";
  else if (s == "or") s = "||";
  o << ' ' << s << ' ';
  assert(op.source2);
  printExpr(op.source2);
  o << ')';
  return Status();
}
```

13b ⟨*declarations* 4a⟩+≡ (2) ◁12b 13c▷

```
Status visit(UnaryOp &);
Status visit(BinaryOp &);
```

5.4 Literal

13c ⟨*declarations* 4a⟩+≡ (2) ◁13b 14a▷

```
Status visit(Literal &);
```

13d ⟨*definitions* 3a⟩+≡ (36c) ◁13a 14b▷

```
Status Printer::visit(Literal &l)
{
  assert(l.type);
  if ( l.type->name == "string" ) {
    o << '\"';
    for ( string::iterator i = l.value.begin() ; i != l.value.end() ; i++ ) {
      if (*i == '\"') o << '\\';
      o << *i;
    }
    o << '\"';
  } else {
    o << l.value;
  }
  return Status();
}
```

5.5 Function Call

Normal function calls are straightforward. Builtin functions are special: they are actually arithmetic or logical operators and therefore printed with an inline notation.

14a ⟨*declarations* 4a⟩+≡ (2) ◁13c 15a▷

```
Status visit(FunctionCall &);
```

14b ⟨*definitions* 3a⟩+≡ (36c) ◁13d 15b▷

```
Status Printer::visit(FunctionCall &c)
{
  assert(c.callee);
  if (dynamic_cast<BuiltinFunctionSymbol*>(c.callee)) {
    o << '(';
    switch (c.arguments.size()) {
    case 1:
      if (c.callee->name == "not") {
        o << '!';
      } else {
        o << c.callee->name << ' ';
      }
      printExpr(c.arguments.front());
      break;
    case 2:
      printExpr(c.arguments.front());
      if ( c.callee->name == "and" ) o << " && ";
      else if (c.callee->name == "or" ) o << " || ";
      else if (c.callee->name == "=" ) o << " == ";
      else if (c.callee->name == "<>" ) o << " != ";
      else o << ' ' << c.callee->name << ' ';
      printExpr(c.arguments[1]);
      break;
    default:
      // Not one or two arguments.  What function is this?
      assert(0);
      break;
    }
    o << ')';
  } else {
    o << c.callee->name << '(';
    for ( vector<Expression*>::iterator i = c.arguments.begin() ;
          i != c.arguments.end() ; i++ ) {
      printExpr(*i);
      if ( i != (c.arguments.end() - 1)) o << ", ";
    }
    o << ')';
  }
  return Status();
}
```

5.6 Procedure Call

15a ⟨*declarations* 4a⟩+≡ (2) ◁14a 15c▷

```
Status visit(ProcedureCall &);
```

15b ⟨*definitions* 3a⟩+≡ (36c) ◁14b 16a▷

```
Status Printer::visit(ProcedureCall &c)
{
  assert(c.procedure);
  o << c.procedure->name << '(';
  bool needComma = false;
  for ( vector<VariableSymbol*>::iterator i = c.reference_args.begin() ;
        i != c.reference_args.end() ; i++ ) {
    assert(*i);
    if (needComma) o << ", ";
    o << '&' << (*i)->name;
    needComma = true;
  }
  for ( vector<Expression*>::iterator i = c.value_args.begin() ;
        i != c.value_args.end() ; i++ ) {
    if (needComma) o << ", ";
    printExpr(*i);
    needComma = true;
  }
  o << ")";
  return Status();
}
```

6 Overall declarations

This decides whether a `#include "basename.h"` is needed and prints it. `printDeclarations` calls this, so there should be no need otherwise.

15c ⟨*declarations* 4a⟩+≡ (2) ◁15a 16b▷

```
virtual void printInclude(string);
```

16a ⟨*definitions* 3a⟩+≡ (36c) ◁15b 17▷

```
void Printer::printInclude(string basename)
{

  // Decide whether to #include "basename.h"
  // If there are any procedures, tasks, user-defined types, functions
  // or undefined constants, include it.
  bool needInclude = (m.procedures->size() != 0) || (m.tasks->size() != 0);

  if ( !needInclude )
    for ( SymbolTable::const_iterator i = m.types->begin() ;
          i != m.types->end() ; i++ )
      if ( dynamic_cast<BuiltinTypeSymbol*>(*i) == NULL ) {
        needInclude = true;
        break;
      }

  if ( !needInclude )
    for ( SymbolTable::const_iterator i = m.constants->begin() ;
          i != m.constants->end() ; i++ )
      if ( dynamic_cast<BuiltinConstantSymbol*>(*i) == NULL) {
        ConstantSymbol *cs = dynamic_cast<ConstantSymbol*>(*i);
        assert(cs);
        if (cs->initializer == NULL) {
          needInclude = true;
          break;
        }
      }

  if ( !needInclude )
    for ( SymbolTable::const_iterator i = m.functions->begin() ;
          i != m.functions->end() ; i++ )
      if ( dynamic_cast<BuiltinFunctionSymbol*>(*i) == NULL) {
        needInclude = true;
        break;
      }

  if (needInclude)
    o << "#include \"" << basename << ".h\"\n";
}
```

7 Declarations for variables, functions, procedures, etc.

16b ⟨*declarations* 4a⟩+≡ (2) ◁15c 25a▷

```
virtual void printDeclarations(string);
```

17 ⟨*definitions* 3a⟩+≡ (36c) ◁16a 25b▷

```
void Printer::printDeclarations(string basename)
{

  // Although external types need no declarations, their names
  // are registered to check for later collisions

  o <<
    "#ifndef STRLEN"          "\n"
    "#  define STRLEN 81"     "\n"
    "#endif"                  "\n"
    "#define _true 1"         "\n"
    "#define _false 0"        "\n"
    "typedef unsigned char boolean;"  "\n"
    "typedef int integer;"   "\n"
    "typedef char* string;"  "\n"
    ;

  printInclude(basename);

  BuiltinConstantSymbol *truec =
    dynamic_cast<BuiltinConstantSymbol*>(m.constants->get(string("true")));
  assert(truec);
  variableVar[truec] =  uniqueID("_true");
  BuiltinConstantSymbol *falsec =
    dynamic_cast<BuiltinConstantSymbol*>(m.constants->get(string("false")));
  assert(falsec);
  variableVar[falsec] = uniqueID("_false");

  identifiers.insert("STRLEN");

  // Verify all exteral type names are OK

  assert(m.types);
  for ( SymbolTable::const_iterator i = m.types->begin() ;
        i != m.types->end() ; i++ ) {
    TypeSymbol *s = dynamic_cast<TypeSymbol*>(*i);
    assert(s);
    if (contains(identifiers, s->name))
      throw IR::Error("Name of external type \"" + s->name +
                      "\" already in use");
    uniqueID(s->name);
  }

  // Print input function declarations

  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
```

```
    assert(s);
    if (s->name != "tick" &&
        ( s->kind == SignalSymbol::Input ||
          s->kind == SignalSymbol::Inputoutput)) {
      assert(m.symbol);
      o << "void " << m.symbol->name << "_I_" << s->name << "(";
      if (s->type) {
        o << s->type->name;
      } else {
        o << "void";
      }
      o << ");\n";
    }
  }

  // Print declarations for the tick and reset functions

  o <<
    "int " << m.symbol->name << "(void);"        "\n"
    "int " << m.symbol->name << "_reset(void);"  "\n";

  // External declarations (constants, functions, procedures)

  o << "#ifndef _NO_EXTERN_DEFINITIONS"    "\n";

  // Uninitialized constants

  o << "#  ifndef _NO_CONSTANT_DEFINITIONS"   "\n";
  assert(m.constants);
  for ( SymbolTable::const_iterator i = m.constants->begin() ;
        i != m.constants->end() ; i++ ) {
    ConstantSymbol *s = dynamic_cast<ConstantSymbol*>(*i);
    assert(s);
    if (!s->initializer) {
      o << "#    ifndef _" << s->name << "_DEFINED\n";
      o << "#      ifndef " << s->name << "\n";
      assert(s->type);
      if (contains(identifiers, s->name))
        throw IR::Error("Name of constant \"" + s->name + "\" already in use");
      string var = uniqueID(s->name);
      variableVar[s] = var;
      o << "extern " << s->type->name << " " << var << ";\n";
      o << "#      endif\n";
      o << "#    endif\n";
    }
  }
  o << "#  endif /* _NO_CONSTANT_DEFINITIONS */\n";

  // Functions
```

```
o << "#  ifndef _NO_FUNCTION_DEFINITIONS"   "\n";
assert(m.functions);
for ( SymbolTable::const_iterator i = m.functions->begin() ;
      i != m.functions->end() ; i++ ) {
  FunctionSymbol *s = dynamic_cast<FunctionSymbol*>(*i);
  assert(s);
  if (dynamic_cast<BuiltinFunctionSymbol*>(*i) == NULL ) {
    o << "#    ifndef _" << s->name << "_DEFINED\n";
    o << "#      ifndef " << s->name << "\n";
    if (contains(identifiers, s->name))
      throw IR::Error("Name of function \"" + s->name + "\" already in use");
    uniqueID(s->name);
    assert(s->result);
    o << "extern " << s->result->name << " " << s->name << "(";
    if (s->arguments.empty()) {
      o << "void";
    } else {
      for ( vector<TypeSymbol*>::const_iterator j = s->arguments.begin() ;
            j != s->arguments.end() ; j++ ) {
        assert(*j);
        o << (*j)->name;
        if ( j != s->arguments.end() - 1) o << ", ";
      }
    }
    o << ");\n";
    o << "#      endif\n";
    o << "#    endif\n";
  }
}
o << "#  endif /* _NO_FUNCTION_DEFINITIONS */\n";

// Procedures

o << "#  ifndef _NO_PROCEDURE_DEFINITIONS"   "\n";
assert(m.procedures);
for ( SymbolTable::const_iterator i = m.procedures->begin() ;
      i != m.procedures->end() ; i++ ) {
  ProcedureSymbol *s = dynamic_cast<ProcedureSymbol*>(*i);
  assert(s);
  o << "#    ifndef _" << s->name << "_DEFINED\n";
  o << "#      ifndef " << s->name << "\n";
  if (contains(identifiers, s->name))
    throw IR::Error("Name of procedure \"" + s->name + "\" already in use");
  uniqueID(s->name);
  o << "extern void " << s->name << "(";
  for ( vector<TypeSymbol*>::const_iterator j =
          s->reference_arguments.begin() ;
        j != s->reference_arguments.end() ; j++ ) {
    assert(*j);
    o << (*j)->name << "*";
```

```
      if ( j != s->reference_arguments.end() - 1 ||
           !s->value_arguments.empty() )
        o << ", ";
    }
    for ( vector<TypeSymbol*>::const_iterator j = s->value_arguments.begin() ;
          j != s->value_arguments.end() ; j++ ) {
      assert(*j);
      o << (*j)->name;
      if ( j != s->value_arguments.end() - 1) o << ", ";
    }
    o << ");\n";
    o << "#      endif\n";
    o << "#    endif\n";
  }
  o << "#  endif /* _NO_PROCEDURE_DEFINITIONS */\n";

  o << "#endif /* _NO_EXTERN_DEFINITIONS */\n\n";

  // Initialized Constants

  for ( SymbolTable::const_iterator i = m.constants->begin() ;
        i != m.constants->end() ; i++ ) {
    ConstantSymbol *s = dynamic_cast<ConstantSymbol*>(*i);
    assert(s);
    if (s->initializer && dynamic_cast<BuiltinConstantSymbol*>(*i) == NULL) {
      assert(s->type);
      if (contains(identifiers, s->name))
        throw IR::Error("Name of constant \"" + s->name + "\" already in use");
      string var = uniqueID(s->name);
      variableVar[s] = var;
      o << "static " << s->type->name << " " << s->name << " = ";
      printExpr(s->initializer);
      o << ";\n";
    }
  }

  // Variables for signal declarations

#ifdef USE_STRUCTS_FOR_SIGNALS
  assert(m.signals);

  // Define a struct holding all boolean presence variables

  o << "static struct {\n";
  unsigned int n_signals = 0;
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->name != "tick") {
```

```
      // All signals, sensors included, have presence variables
      string var = uniqueID(s->name);
      o << "  unsigned int " << var << " : 1;\n";
      presenceVar[s] = string("_s.") + var;
      ++n_signals;
    }
  }
  o << "} _s = { ";
  for (unsigned int i = 0 ; i < n_signals ; i++) {
    o << " 0";
    if ( i < n_signals - 1 ) o << ", ";
  }
  o << " };\n";

  // Define value variables for each valued signal

  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->name == "tick") {
      // "tick" is a special built-in signal that is always present
      string var = uniqueID(s->name);
      presenceVar[s] = var;
      o << "#define " << var << " 1\n";
    }
    if (s->type) {
      // Has a type: need a value variable
      string var = uniqueID(s->name + "_v");
      valueVar[s] = var;
      o << "static ";
      if (s->type->name == "string")
        o << "char " << var << "[STRLEN]";
      else
        o << s->type->name << " " << var;
      o << ";\n";
    }
  }

#else

  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->name == "tick") {
      // "tick" is a special built-in signal that is always present
      string var = uniqueID(s->name);
      presenceVar[s] = var;
```

```
      o << "#define " << var << " 1\n";
    } else {
      // All signals, sensors included, have presence variables
      string var = uniqueID(s->name);
      presenceVar[s] = var;
      o << "static boolean " << var << " = _false;\n";
    }
    if (s->type) {
      // Has a type: need a value variable
      string var = uniqueID(s->name + "_v");
      valueVar[s] = var;
      o << "static ";
      if (s->type->name == "string")
        o << "char " << var << "[STRLEN]";
      else
        o << s->type->name << " " << var;
      o << ";\n";
    }
  }

#endif

  // Variable declarations

  assert(m.variables);
  for ( SymbolTable::const_iterator i = m.variables->begin() ;
        i != m.variables->end() ; i++ ) {
    VariableSymbol *s = dynamic_cast<VariableSymbol*>(*i);
    assert(s);
    string var = uniqueID(s->name);
    variableVar[s] = var;
    o << "static ";
    if ( s->type->name == "string" )
      o << "char " << var << "[STRLEN]";
    else
      o << s->type->name << ' ' << var;
    if ( s->initializer ) {
      o << " = ";
      printExpr(s->initializer);
    }
    o << ";\n";
  }

  // State variable declarations

#ifdef USE_STRUCTS_FOR_STATES

  o << "static struct {\n";
  for ( STmap::const_iterator i = stmap.begin() ; i != stmap.end() ; i++ ) {
    STexcl *e = dynamic_cast<STexcl*>((*i).first);
```

```
    if (e) {
      char buf[15];
      sprintf(buf, "_%d", stmap[e]);
      stateVar[e] = string("_state.") + string(buf);
      unsigned int bits = 1;
      while ( (1 << bits) < e->children.size() ) ++bits;
      o << "  unsigned int " << buf << " : " << bits << ";\n";
    }
  }
  o << "} _state = { ";
  bool needComma = false;
  for ( STmap::const_iterator i = stmap.begin() ; i != stmap.end() ; i++ ) {
    STexcl *e = dynamic_cast<STexcl*>((*i).first);
    if (e) {
      // Initialization of states
      if (needComma) o << ", ";
      o << (e->children.size() - 1);
      needComma = true;
    }
  }
  o << " };\n";

#else

  for ( STmap::const_iterator i = stmap.begin() ; i != stmap.end() ; i++ ) {
    STexcl *e = dynamic_cast<STexcl*>((*i).first);
    if (e) {
      char buf[15];
      sprintf(buf, "_state_%d", stmap[e]);
      string var = uniqueID(buf);
      stateVar[e] = var;
      o << "static unsigned char " << var;
      // Initialization of state of selection-tree root:
      //   state = highest-numbered child
      if ( e == g->selection_tree )
        o << " = " << (e->children.size() - 1);
      o << ";\n";
    }
  }
#endif

  // Termination level variable declarations

    for ( CFGmap::const_iterator i = cfgmap.begin() ;
          i != cfgmap.end() ; i++ ) {
    Sync *s = dynamic_cast<Sync*>((*i).first);
    if (s) {

      // Count the number of non-zero successors
```

```
      unsigned int successors = 0;
      for ( vector<GRCNode*>::iterator j = s->successors.begin() ;
            j != s->successors.end() ; j++ )
        if (*j) ++successors;
      if (successors > 1) {
        // If there is more than one non-NULL successor, generate a variable
        char buf[15];
        sprintf(buf, "_term_%d", cfgmap[s]);
        string var = uniqueID(buf);
        terminationVar[s] = var;
        o << "static int " << var << ";\n";
      }
    }
  }

  // Counter declarations

  for ( vector<Counter*>::const_iterator i = m.counters.begin() ;
        i != m.counters.end() ; i++ ) {
    char buf[15];
    sprintf(buf, "_counter_%d", i-m.counters.begin() );
    string var = uniqueID(buf);
    counterVar[*i] = var;
    o << "static int " << var << ";\n";
  }


#ifdef PRINT_OUTPUT_FUNCTION_DECLARATIONS
  // Output function declarations

  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->kind == SignalSymbol::Output ||
        s->kind == SignalSymbol::Inputoutput) {
      string name = m.symbol->name + "_O_" + s->name;
      o << "#ifndef " << name << "\n"
        "extern void " << name << "(";
      if (s->type) o << s->type->name;
      else o << "void";
      o << ");\n"
        "#endif\n";
    }
  }
#endif

}
```

8 Output Functions

Generate code that check the signal presence variables and call output functions as appropriate.

25a ⟨*declarations* 4a⟩+≡ (2) ◁16b 25c▷

```
virtual void outputFunctions();
```

25b ⟨*definitions* 3a⟩+≡ (36c) ◁17 26a▷

```
void Printer::outputFunctions()
{
  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->kind == SignalSymbol::Output ||
        s->kind == SignalSymbol::Inputoutput) {
      assert(contains(presenceVar, s));
      o << "  if (" << presenceVar[s] << ") { ";
      o << m.symbol->name << "_O_" << s->name << "(";
      if (s->type) {
        assert(contains(valueVar, s));
        o << valueVar[s];
      }
      o << "); " << presenceVar[s] << " = 0; }\n";
    }
  }
}
```

9 Reset inputs

Generate code that resets all the inputs and sensor presence variables.

25c ⟨*declarations* 4a⟩+≡ (2) ◁25a 26b▷

```
virtual void resetInputs();
```

26a ⟨*definitions* 3a⟩+≡ (36c) ◁25b 27▷

```
void Printer::resetInputs()
{
  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);
    if (s->name != "tick" &&
        ( s->kind == SignalSymbol::Input ||
          s->kind == SignalSymbol::Inputoutput ||
          s->kind == SignalSymbol::Sensor )) {
      o << "  ";
      assert(contains(presenceVar, s));
      o << presenceVar[s] << " = 0;\n";
    }
  }
}
```

10 I/O function printers

FIXME: This does not support “combine” functions.

26b ⟨*declarations* 4a⟩+≡ (2) ◁25c 28a▷

```
virtual void ioDefinitions();
```

27 ⟨*definitions* 3a⟩+≡ (36c) ◁26a 28b▷

```
void Printer::ioDefinitions()
{
  // Print input signal function definitions

  assert(m.signals);
  for ( SymbolTable::const_iterator i = m.signals->begin() ;
        i != m.signals->end() ; i++ ) {
    SignalSymbol *s = dynamic_cast<SignalSymbol*>(*i);
    assert(s);

    if (s->name != "tick" &&
        ( s->kind == SignalSymbol::Input ||
          s->kind == SignalSymbol::Inputoutput)) {
      assert(contains(presenceVar, s));
      assert(m.symbol);
      o << "void " << m.symbol->name << "_I_" << s->name << "(";
      if (s->type) {
        o << s->type->name << " _v";
      } else {
        o << "void";
      }
      o << ") {\n"
        "  " << presenceVar[s] << " = 1;\n";
      if (s->type) {
        assert(contains(valueVar, s));
        if (s->type->name == "string") {
          o << "  strcpy(" << valueVar[s] << ", _v);\n";
        } else {
          // FIXME: This doesn't work with combine
          o << "  " << valueVar[s] << " = _v;\n";
        }
      }
      o << "}\n";
    }
  }
}
```

11 Structured Code Generation

This prints C code for an acyclic CFG using the algorithm described in Stephen A. Edwards, An Esterel Compiler for Control-Dominated Systems, *IEEE Transactions on CAD*, 21(2), February 2002. It first constructs a reverse immediate dominator tree to determine where to terminate block-structured statements such as if-else and switch. Then it uses a recursive procedure to construct a simple abstract syntax tree for the generated code. Finally, this tree is walked to generate the final code.

The node passed the `printStructuredCode` should be the *exit* node for the CFG to be printed, i.e., it should have no successors.

28a ⟨*declarations* 4a⟩+≡ (2) ◁26b 29a▷

```
void printStructuredCode(GRCNode *, unsigned int = 0);
```

28b ⟨*definitions* 3a⟩+≡ (36c) ◁27 29b▷

```
void Printer::printStructuredCode(GRCNode *exit_node, unsigned int indent)
{
  assert(exit_node);
  assert(exit_node->successors.size() == 0);

  // Number the nodes in a depth-first order

  nodes.clear();
  nodeNumber.clear();

  dfsVisit(exit_node);

  ⟨compute reverse dominators 30⟩

  GRCNode *entry_node = nodes.front();

  statementFor.clear();
  CStatement *root = synthesize(entry_node, nodes.back(), false);

  CStatement::printer = this;
  for ( ; root ; root = root->next ) {
    // std::cerr << "Printing node " << cfgmap[root->node] << "\n";
    root->print(indent);
  }

  delete root;
}
```

11.1 DFS node numbering

This method computes the postorder numbering of nodes required by the dominator algorithm.

29a ⟨*declarations* 4a⟩+≡ (2) ◁28a 33e▷

```
void dfsVisit(GRCNode*);
```

29b ⟨*definitions* 3a⟩+≡ (36c) ◁28b 32a▷

```
void Printer::dfsVisit(GRCNode *n)
{
  if (!n || nodeNumber.find(n) != nodeNumber.end()) return;
  nodeNumber[n] = -1; // Mark as being visited, but do not know number yet

  for (vector<GRCNode*>::const_iterator i = n->predecessors.begin() ;
       i != n->predecessors.end() ; i++)
    dfsVisit(*i);

  nodeNumber[n] = nodes.size();
  nodes.push_back(n);

  // std::cerr << "Assigned node " << cfgmap[n] << " = " << nodeNumber[n] << '\n';
}
```

11.2 Compute Reverse Dominators

This uses the iterative dominator computation algorithm from Keith Cooper, Timothy Harvey, and Ken Kennedy, *A Simple, Fast Dominance Algorithm*, submitted to Software—Practice and Experience.

30 ⟨*compute reverse dominators* 30⟩≡ (28b)

```
ridom.clear();

// Compute immediate dominators on the reverse graph

ridom[exit_node] = exit_node;
bool changed;
do {
  changed = false;
  for ( vector<GRCNode*>::reverse_iterator b = nodes.rbegin() + 1;
        b != nodes.rend() ; b++ ) {
    GRCNode *new_idom = NULL;
    for ( vector<GRCNode*>::iterator p = (*b)->successors.begin() ;
          p != (*b)->successors.end() ; p++ ) {
      if ( ridom.find(*p) != ridom.end() ) {
        if ( new_idom == NULL )
          new_idom = *p;
        else {
          // Intersect
          GRCNode *b1 = *p;
          GRCNode *b2 = new_idom;
          while (b1 != b2) {
            while (nodeNumber[b1] < nodeNumber[b2]) b1 = ridom[b1];
            while (nodeNumber[b2] < nodeNumber[b1]) b2 = ridom[b2];
          }
          new_idom = b1;
        }
      }
    }
    if ( ridom[*b] != new_idom ) {
      ridom[*b] = new_idom;
      // std::cerr << "idom of " << cfgmap[*b] << " is " << cfgmap[new_idom] << '\n';
      changed = true;
    }
  }
} while (changed);
```

11.3 C Statements

31 ⟨*c statement classes* 31⟩≡ (36b)

```
class Printer;

struct CStatement {
  static Printer *printer;

  GRCNode *node;
  CStatement *next;
  string label;

  CStatement(GRCNode *node) : node(node), next(0) {}
  virtual ~CStatement() { delete next; }
  virtual void print(unsigned int = 0);
  void indent(unsigned int);
  void begin(unsigned int);
};

struct CIfElse : CStatement {
  CStatement *thenSt;
  CStatement *elseSt;
  CIfElse(GRCNode *node, CStatement *thenSt, CStatement *elseSt)
    : CStatement(node), thenSt(thenSt), elseSt(elseSt) {}
  virtual ~CIfElse() { delete thenSt; delete elseSt; }
  void print(unsigned int = 0);
};

struct CGoto : CStatement {
  string label;
  CGoto(string label) : CStatement(NULL), label(label) {}
  void print(unsigned int = 0);
};

struct CBreak : CStatement {
  CBreak() : CStatement(NULL) {}
  void print(unsigned int = 0);
};

struct CSwitch : CStatement {
  CStatement *body;
  CSwitch(GRCNode *node, CStatement *body) : CStatement(node), body(body) {}
  virtual ~CSwitch() { delete body; }
  void print(unsigned int = 0);
};

struct CCase : CStatement {
  int label;
  CStatement *body;
  CCase(int label, CStatement *body) : CStatement(NULL), label(label), body(body) {}
```

```
  void print(unsigned int = 0);
};
```

32a ⟨*definitions* 3a⟩+≡ (36c) ◁29b 32b▷

```
Printer *CStatement::printer = 0;
```

32b ⟨*definitions* 3a⟩+≡ (36c) ◁32a 32c▷

```
void CStatement::indent(unsigned int n)
{
  for (unsigned int i = 0 ; i < n ; i++) printer->o << "  ";
}
```

32c ⟨*definitions* 3a⟩+≡ (36c) ◁32b 32d▷

```
void CStatement::begin(unsigned int i)
{
  if (!label.empty()) {
    indent(i > 0 ? i - 1 : i);
    printer->o << label << ":\n";
  }
  indent(i);
}
```

32d ⟨*definitions* 3a⟩+≡ (36c) ◁32c 32e▷

```
void CStatement::print(unsigned int i)
{
  begin(i);
  printer->printExpr(node);
  printer->o << ";\n";
}
```

32e ⟨*definitions* 3a⟩+≡ (36c) ◁32d 33a▷

```
void CIfElse::print(unsigned int i)
{
  begin(i);
  printer->o << "if (";
  printer->printExpr(node);
  printer->o << ") {\n";
  for ( CStatement *st = thenSt ; st ; st = st->next ) st->print(i+1);
  indent(i);
  printer->o << "}";
  if ( elseSt ) {
    printer->o << " else {\n";
    for ( CStatement *st = elseSt ; st ; st = st->next ) st->print(i+1);
    indent(i);
    printer->o << "}\n";
  } else {
    printer->o << "\n";
  }
}
```

33a ⟨*definitions* 3a⟩+≡ (36c) ◁32e 33b▷
```
void CGoto::print(unsigned int i)
{
  begin(i);
  printer->o << "goto " << label << ";\n";
}
```

33b ⟨*definitions* 3a⟩+≡ (36c) ◁33a 33c▷
```
void CBreak::print(unsigned int i)
{
  begin(i);
  printer->o << "break;\n";
}
```

33c ⟨*definitions* 3a⟩+≡ (36c) ◁33b 33d▷
```
void CSwitch::print(unsigned int i)
{
  begin(i);
  printer->o << "switch (";
  printer->printExpr(node);
  printer->o << ") {\n";
  for ( CStatement *st = body ; st ; st = st->next ) st->print(i+1);
  indent(i);
  printer->o << "default: break;\n";
  indent(i);
  printer->o << "}\n";
}
```

33d ⟨*definitions* 3a⟩+≡ (36c) ◁33c 34▷
```
void CCase::print(unsigned int i)
{
  indent(i > 0 ? i - 1 : 0);
  printer->o << "case " << label << ":\n";
  assert(body);
  for ( CStatement *st = body ; st ; st = st->next ) st->print(i);
}
```

11.4 Statement synthesis

33e ⟨*declarations* 4a⟩+≡ (2) ◁29a
```
CStatement *synthesize(GRCNode*, GRCNode*, bool);
```

34 ⟨*definitions* 3a⟩+≡ (36c) ◁33d

```
CStatement *Printer::synthesize(GRCNode *node, GRCNode *final, bool needBreak)
{
  assert(node);
  assert(final);

  // std::cerr << "/* initial synthesize(" << cfgmap[node] << ", " << cfgmap[final] << ", " <<

  if ( node == final )
    return needBreak ? new CBreak() : 0;

  if ( statementFor.find(node) != statementFor.end() ) {
    CStatement *target = statementFor[node];
    if (target->label.empty()) {
      char buf[20];
      // sprintf(buf, "L%d", nextLabel++);
      assert(cfgmap.find(node) != cfgmap.end());
      sprintf(buf, "N%d", cfgmap[node]);
      target->label = buf;
    }
    return new CGoto(target->label);
  }

  assert(ridom.find(node) != ridom.end());

  GRCNode *next =
    (node->successors.size() > 1) ? ridom[node] : node->successors.front();

  CStatement *nextStatement = next ? synthesize(next, final, needBreak) : 0;

  // std::cerr << "/* continue synthesize(" << cfgmap[node] << ", " << cfgmap[final] << ", " <

  CStatement *result = NULL;

  switch (node->successors.size()) {
  case 0:
  case 1:
    // std::cerr << "simple statement\n";
    result = new CStatement(node);
    break;
  case 2:
    {
      if (node->successors.front() && node->successors.back()) {
        // std::cerr << "if-then-else statement\n";
        CStatement *elsePart =
          synthesize(node->successors.front(), next, false);
        CStatement *thenPart =
          synthesize(node->successors.back(), next, false);
        result = new CIfElse(node, thenPart, elsePart);
      } else {
```

```
        result = new CStatement(new Nop());
      }
    }
    break;
  default:
    // Three or more successors: a switch statement
    {
      unsigned int nonzero_successors = 0;
      for ( vector<GRCNode*>::reverse_iterator i = node->successors.rbegin() ;
            i != node->successors.rend() ; i++ )
        if (*i) ++nonzero_successors;
      if (nonzero_successors > 1) {
        CStatement *body = NULL;
        bool useSyncNumbering = dynamic_cast<Sync*>(node) != NULL;
        for ( vector<GRCNode*>::reverse_iterator i =
                node->successors.rbegin() ;
              i != node->successors.rend() ; i++ )
          if (*i) {
            CStatement *caseBody = synthesize(*i, next, true);
            int caseLabel = node->successors.rend() - i - 1;
            if (useSyncNumbering) caseLabel = (1 << caseLabel) - 1;
            CStatement *thisCase = new CCase(caseLabel, caseBody);
            thisCase->next = body;
            body = thisCase;
          }
        result = new CSwitch(node, body);
      } else {
        result = new CStatement(new Nop());
      }
    }
    break;
  }

  assert(result);
  assert(result->next == NULL);
  result->next = nextStatement;

  // std::cerr << "done with " << cfgmap[node] << "\n";
  assert(result);
  statementFor[node] = result;
  if (labelFor.find(node) != labelFor.end())
    result->label = labelFor[node];
  return result;
}
```

12 Utilities

36a ⟨*utilities* 36a⟩≡ (36b)

```
template <class T> bool contains(set<T> &s, T o) {
   return s.find(o) != s.end();
}

template <class T, class U> bool contains(map<T, U> &m, T o) {
  return m.find(o) != m.end();
}
```

13 Top-Level Files

36b ⟨*CPrinter.hpp* 36b⟩≡

```
#ifndef _CPRINTER_HPP
#  define _CPRINTER_HPP

#  define USE_STRUCTS_FOR_SIGNALS
/* #  define USE_STRUCTS_FOR_STATES */

#  include "AST.hpp"
#  include <iostream>
#  include <cassert>
#  include <set>
#  include <vector>
#  include <map>

namespace CPrinter {
  using namespace AST;
  using std::set;
  using std::vector;
  using std::map;

  ⟨utilities 36a⟩

  ⟨c statement classes 31⟩

  ⟨printer class 2⟩
}

#endif
```

36c ⟨*CPrinter.cpp* 36c⟩≡

```
#include "CPrinter.hpp"
#include <stdio.h>

namespace CPrinter {
  ⟨definitions 3a⟩
}
```