From Data to Effects Dependence Graphs: Source-to-Source Transformations for C

SCAM 2016

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Source-to-Source Compilers

- Fortran code
- C code

```c
int main() {
  int i=10, j=1;
  int k = 2*(2*i+j);

  return k;
}
```

- Static analyses
- Instrumentation/ Dynamic analyses
- Transformations
- Source code generation
- Code modelling
- Prettyprint

- Fortran code
- C code

```c
//PRECONDITIONS
int main() {
//  P() {}
   int i = 10, j = 1;

//  P(i,j) {i==10, j==1}
   int k = 2*(2*i+j);

//  P(i,j,k) {i==10,
j==1, k==42}
   return k;
}
```

Loop Distribution on C99 Code

```
void example(unsigned int n)
{
   int a[n], b[n];
   for(int i=0; i<n; i++) {
      a[i] = i;
      typedef int mytype;
      mytype x;
      x = i;
      b[i] = x;
   }
   return;
}
```

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void example(unsigned int n)
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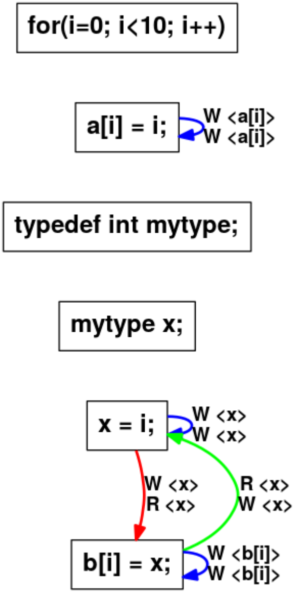
    for(int i=0; i<n; i++) {
        a[i] = i;
        typedef int mytype;
        mytype x;
        x = i;
        b[i] = x;
    }
    return;
}
```

```c
void example(unsigned int n)
{
    int a[n], b[n];
    {
        int i;
        for(i = 0; i < n; i += 1) {
            a[i] = i;
        }
        for(i = 0; i < n; i += 1) {
            typedef int mytype;
        }
        for(i = 0; i < n; i += 1) {
            mytype x;
        }
        for(i = 0; i < n; i += 1) {
            x = i;
            b[i] = x;
        }
    }
    return;
}
```

Data Dependence Graph

```
void example(unsigned int n)
{
    int a[n], b[n];
    for(int i=0; i<n; i++) {
        a[i] = i;
        typedef int mytype;
        mytype x;
        x = i;
        b[i] = x;
    }
    return;
}
```



Outline

1. Limitations of the Data Dependence Graph
2. Effects Dependence Graph
3. Impact on Existing Code Transformations

Data Dependence Graph

- constraints on memory accesses for preventing incorrect reordering of operations/statements/loop iterations
- 3 types of constraints
  - flow dependence: read after write
  - anti-dependence: write after read
  - output dependence: write after write
- Limitations with C99

  declarations anywhere references after declaration

  user-defined types anywhere variable declaration after type declaration

  dependent types type write after variable write

Workarounds

Flatten Declarations

- Move every declarations at the function scope

Frame Pointer

- Use a low-level representation for the memory allocations

Flatten Declarations

Principle

- Move declarations at the function scope
- Perform α-*renaming* when necessary

Advantage

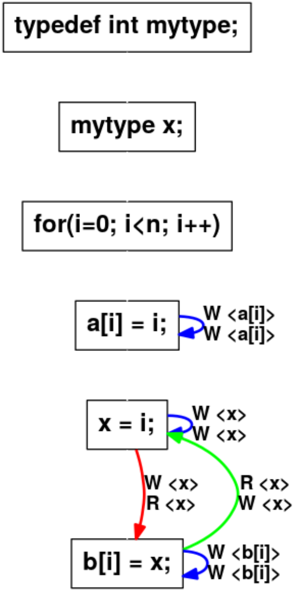
- Implementation is easy

Drawbacks

- Source code altered and less readable
- Possible stack overflow
- Not compatible with dependent types

Code Flattening

```
void example(unsigned int n)
{
   int a[n], b[n];
   int i;
   typedef int mytype;
   mytype x;
   for(i = 0; i < n; i += 1) {
      a[i] = i;
      x = i;
      b[i] = x;
   }
   return;
}
```



Code Flattening

```
void example(unsigned int n)
{
   int a[n], b[n];
   int i;
   typedef int mytype;
   mytype x;
   for(i = 0; i < n; i += 1) {
      a[i] = i;
      x = i;
      b[i] = x;
   }
   return;
}
```

```
void example(unsigned int n)
{
   int a[n], b[n];
   int i;
   typedef int mytype;
   mytype x;
   for(i = 0; i < n; i += 1)
      a[i] = i;
   for(i = 0; i < n; i += 1) {
      x = i;
      b[i] = x;
   }
   return;
}
```

Code Flattening & Dependent Type

```c
void example(unsigned int n)
{
    int m;
    m = n+1;
    {
        int a[m], b[m];
        for(int i=0; i<m; i++) {
            a[i] = i;
            typedef int mytype;
            mytype x;
            x = i;
            b[i] = x;
        }
    }
    return;
}
```

```c
void example(unsigned int n)
{
    int m;
    int a[m], b[m];
    int i;
    typedef int mytype;
    mytype x;
    m = n+1;
    for(i = 0; i < m; i += 1) {
        a[i] = i;
        x = i;
        b[i] = x;
    }
    return;
}
```

Explicit Memory Access Mechanism

Principle

- Type management:
  - Add a hidden variable ($*type*) to represent the size in bytes of the type.
- Variable management:
  - Add a hidden variable (*fp*) that points to a memory location.
  - For each declaration, compute the address with *fp*.
  - Whenever a variable is referenced, pass by its address to analyze it.

Advantage

- Similar to compiler assembly code

Drawbacks

- New hidden variables added in IR → possible problem of coherency
- Overconstrained → declarations are serialized
- Hard to regenerate high-level source code

Explicit Access Mechanism, Implementation Idea

Initial Code:

```
void example(unsigned int n)
{

 int a[n], b[n];



 {
  int i;

  for(i=0;i<n;i+=1){
   a[i] = i;
   typedef int mytype;
   mytype x;

   x = i;
   b[i] = x;
  }
 }
 return;
}
```

Possible IR:

```
void example(unsigned int n)
{
 void* fp=...;
 a = fp;
 fp -= n*$int;
 b = fp;
 fp -= n*$int;
 {
  &i = fp;
  fp -= $int;
  for(*(&i)=0;*(&i)<n;*(&i)+=1) {
   a[*(&i)] = *(&i);
   $mytype = $int;
   &x = fp;
   fp -= $mytype;
   *(&x) = *(&i);
   b[*(&i)] = *(&x);
  } fp += $mytype;
 } fp += $int;
 return;
}
```

Background – Effects

$$\text{Identifier} \xrightarrow{\ \rho\ } \text{Location} \xrightarrow{\ \sigma\ } \text{Value}$$

```
int x = 0;
```

- *Identifier*, *Location*, *Value*
- **Environment**, *Env* ρ: *Identifier* $\to$ *Location*
- **Memory State**, *MemState* σ: *Location* $\to$ *Value*
- **Statement** S: *Env* $\times$ *MemState* $\to$ *Env* $\times$ *MemState*
- **Memory Effect** E:
  Statement $\to$ *Env* $\times$ *MemState* $\to \mathcal{P}($*Location*$)$
  - Read Effect E_R
  - Write Effect E_W

Our Solution: New Kinds of Effects

Environment and Type Effects

- Environment
  - Read for each access of a variable
  - Write for each declaration of variable
- Type
  - Read for each use of a defined type
  - Write for each `typedef`, `struct`, `union` and `enum`

Our Solution: New Kinds of Effects

Environment and Type Effects

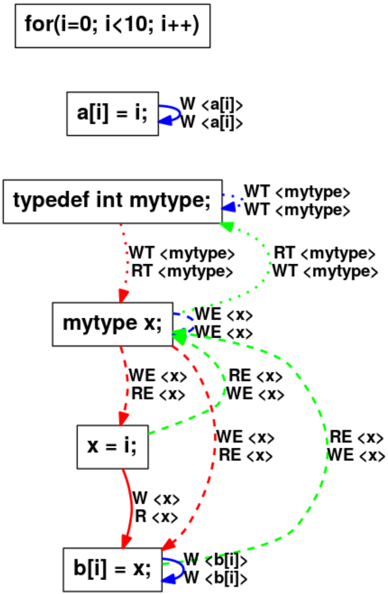
- Environment
  - Read for each access of a variable
  - Write for each declaration of variable
- Type
  - Read for each use of a defined type
  - Write for each `typedef`, `struct`, `union` and `enum`

Effects Dependence Graph (FXDG)

DDG + Environment & Type Effects

- No source code alteration
- More constraints to schedule statements properly
- Some code transformations need to be adapted

Loop Distribution With Extended Effects

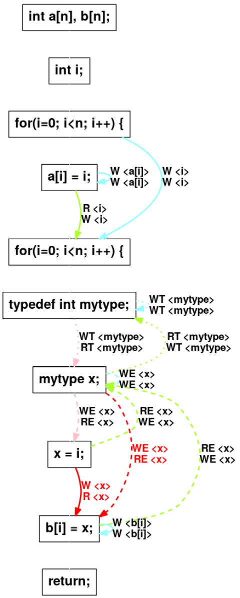



```c
void example(unsigned int n)
{
    int a[n], b[n];
    {
        int i;
        for(i = 0; i < n; i += 1) {
            a[i] = i;
        }
        for(i = 0; i < n; i += 1) {
            typedef int mytype;
            mytype x;
            x = i;
            b[i] = x;
        }
    }
    return;
}
```

Impact of FXDG

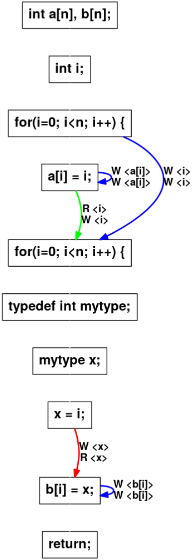
- Transformations benefitting from the FXDG
  - Allen & Kennedy
  - Loop Distribution
  - Dead Code Elimination
- Transformations hindered by the new effects
  - Forward Substitution
  - Scalarization
  - Isolate Statement
- Transformations needing further work
  - Flatten Code
  - Loop Unrolling
  - Loop-Invariant Code Motion
- Transformations not impacted
  - Strip Mining
  - Coarse Grain Parallelization

Forward Substitution with Extended Effects




```c
void example(unsigned int n)
{
    int a[n], b[n];
    {
        int i;
        for(i = 0; i < n; i += 1) {
            a[i] = i;
        }
        for(i = 0; i < n; i += 1) {
            typedef int mytype;
            mytype x;
            x = i;
            b[i] = x;
        }
    }
    return;
}
```

Forward Substitution, Filtering the New Effects




```
void example(unsigned int n)
{
    int a[n], b[n];
    {
        int i;
        for(i = 0; i < n; i += 1) {
            a[i] = i;
        }
        for(i = 0; i < n; i += 1) {
            typedef int mytype;
            mytype x;
            x = i;
            b[i] = i;
        }
    }
    return;
}
```

Related Work

Other Source-to-Source Compilers

- **OSCAR** Fortran Code only
- **Cetus** C89 code only
- **Pluto** not compatible with declarations anywhere
- **Rose** C99 support through the EDG front-end

Low-level Source-to-Source Compilers

- **Polly** LLVM IR $\rightarrow$ LLVM IR

Conclusion

Standard data dependency is not enough

- no constraints on variable/type declarations
- C is too flexible

Effects Dependence Graph

- new Environment and Type Effects
- DDG extension

Impact on code transformations

- direct benefits: Loop Distribution, ...
- need to filter: Forward Substitution, ...
- affected in more complex ways.

$\Longrightarrow$ **different transformations need different Dependence Graphs**

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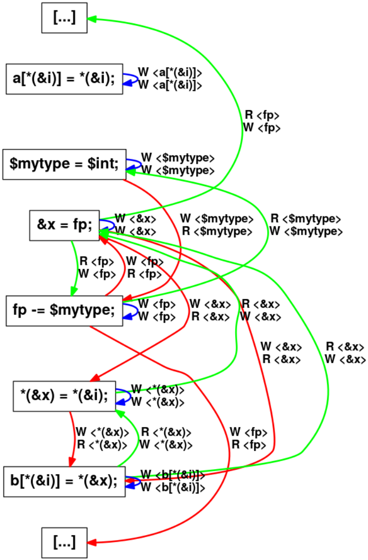
Environment and Type Effect Syntax in PIPS

```
+   action_kind = store:unit + environment:unit + type_declaration:unit ;
-   action = read:unit + write:unit ;
+   action = read:action_kind + write:action_kind ;
    syntax = reference + [...] ;
    expression = syntax ;
    entity = name:string x [...] ;
    reference = variable:entity x indices:expression* ;
    cell = reference + [...] ;
    effect = cell x action x [...] ;
    effects = effects:effect* ;
```

Frame pointer: DDG

```
void example(unsigned int n)
{
 void* fp=...;
 a = fp;
 fp -= n*$int;
 b = fp;
 fp -= n*$int;
 {
  &i = fp;
  fp -= $int;
  for(*(&i)=0;*(&i)<n;*(&i)+=1
   a[*(&i)] = *(&i);
   $mytype = $int;
   &x = fp;
   fp -= $mytype;
   *(&x) = *(&i);
   b[*(&i)] = *(&x);
  } fp += $mytype;
 } fp += $int;
 return;
}
```



VLA Example

Initial Code

```
void foo(int n) {
  int a[n];
  /* ... */
}
```

ASM Code

```
;int a[n];
  mov     -0x24(%rbp),%eax
  movslq  %eax,%rdx
  sub     $0x1,%rdx
  mov     %rdx,-0x18(%rbp)
  movslq  %eax,%rdx
  mov     %rdx,%r10
  mov     $0x0,%r11d
  movslq  %eax,%rdx
  mov     %rdx,%r8
  mov     $0x0,%r9d
  cltq
  shl     $0x2,%rax
  lea     0x3(%rax),%rdx
  mov     $0x10,%eax
  sub     $0x1,%rax
  add     %rdx,%rax
  mov     $0x10,%esi
  mov     $0x0,%edx
  div     %rsi
  imul    $0x10,%rax,%rax
  sub     %rax,%rsp
  mov     %rsp,%rax
  add     $0x3,%rax
  shr     $0x2,%rax
  shl     $0x2,%rax
  mov     %rax,-0x10(%rbp)
```

VLA Example

LLVM Representation

```
; ModuleID = 'vla.c'

; Function Attrs: nounwind uwtable
define void @foo(i32 %n) #0 {
  %1 = alloca i32, align 4
  %2 = alloca i8*
  store i32 %n, i32* %1, align 4
  %3 = load i32* %1, align 4
  %4 = zext i32 %3 to i64
  %5 = call i8* @llvm.stacksave()
  store i8* %5, i8** %2
  %6 = alloca i32, i64 %4, align 16
  %7 = load i8** %2
  /* ... */
  call void @llvm.stackrestore(i8* %7)
  ret void
}

; Function Attrs: nounwind
declare i8* @llvm.stacksave() #1

; Function Attrs: nounwind
declare void @llvm.stackrestore(i8*) #1
```

LLVM to C Code

```
/* ... */
#if __GNUC__ < 4 /*Old GCC's, or compilers not GCC*/
#define __builtin_stack_save() 0
/*not implemented*/
#define __builtin_stack_restore(X) /*noop*/
#endif

void foo(unsigned int llvm_cbe_n) {
  unsigned int llvm_cbe_tmp__1;
  unsigned char *llvm_cbe_tmp__2;
  unsigned int llvm_cbe_tmp__3;
  unsigned char *llvm_cbe_tmp__4;
  unsigned int *llvm_cbe_tmp__5;
  unsigned char *llvm_cbe_tmp__6;

  *(&llvm_cbe_tmp__1) = llvm_cbe_n;
  llvm_cbe_tmp__3 = *(&llvm_cbe_tmp__1);
  llvm_cbe_tmp__4 = 0;
  *((void**)&llvm_cbe_tmp__4) = __builtin_stack_save();
  *(&llvm_cbe_tmp__2) = llvm_cbe_tmp__4;
  llvm_cbe_tmp__5 = (unsigned int *)
      alloca(sizeof(unsigned int)
        * (((unsigned long long)(unsigned int)
        llvm_cbe_tmp__3)));
  llvm_cbe_tmp__6 = *(&llvm_cbe_tmp__2);
  /* ... */
  __builtin_stack_restore(llvm_cbe_tmp__6);
  return;
}
```