Intermediate code

Registers

Registers can only hold values of the types specified in **BaseType**. Single static assignment (SSA) form is always used for registers; no register may be assigned to twice.

Stack frames

To store larger values or values which must be in memory, stack frame storage can be used. To avoid specifying exact sizes, storage is allocated in slots. The `LdF` operation can be used to retrieve the address of a slot in the stack frame. Similarly the `LdFA` operation can be used to retrieve the address of the arguments to the current function.

Blocks

Blocks are sequences of operations. Each block except for the last block in a function ends with a jump or branch operation. There always exists a "current block" into which operations are written while converting expressions to intermediate code. This block can change depending on sequence points and control flow statements.

Since SSA form is used for registers, each block contains a sequence of ϕ (phi) operations, stored separately from normal operations.

Intermediate code format

Operation	Meaning
`Mov r1 -> r2`	`r1 -> r2`
`CvtC r1 -> r2`	`convert r1 as char -> r2`
`CvtUC r1 -> r2`	`convert r1 as unsigned char -> r2`
`CvtS r1 -> r2`	`convert r1 as short -> r2`
`CvtUS r1 -> r2`	`convert r1 as unsigned short -> r2`
`CvtI r1 -> r2`	`convert r1 as int -> r2`
`CvtUI r1 -> r2`	`convert r1 as unsigned int -> r2`
`CvtL r1 -> r2`	`convert r1 as long -> r2`
`CvtUL r1 -> r2`	`convert r1 as unsigned long -> r2`
`CvtLL r1 -> r2`	`convert r1 as long long -> r2`
`CvtULL r1 -> r2`	`convert r1 as unsigned long long -> r2`
`CvtF r1 -> r2`	`convert r1 as float -> r2`
`CvtD r1 -> r2`	`convert r1 as double -> r2`
`CvtP r1 -> r2`	`convert r1 as void * -> r2`
`Add r1, r2 -> r3`	`r1 + r2 -> r3`
`AddI r1, c2 -> r3`	`r1 + c2 -> r3`
`Sub r1, r2 -> r3`	`r1 - r2 -> r3`
`SubI r1, c2 -> r3`	`r1 - c2 -> r3`
`SubIR r1, c2 -> r3`	`c2 - r1 -> r3`
`Mul r1, r2 -> r3`	`r1 * r2 -> r3`
`MulI r1, c2 -> r3`	`r1 * c2 -> r3`
`MulU r1, r2 -> r3`	`r1 * r2 -> r3 (unsigned multiply)`
`MulUI r1, c2 -> r3`	`r1 * c2 -> r3 (unsigned multiply)`
`Div r1, r2 -> r3`	`r1 / r2 -> r3`
`DivI r1, c2 -> r3`	`r1 / c2 -> r3`
`DivIR r1, c2 -> r3`	`c2 / r1 -> r3`
`DivU r1, r2 -> r3`	`r1 / r2 -> r3 (unsigned divide)`
`DivUI r1, c2 -> r3`	`r1 / c2 -> r3 (unsigned divide)`
`DivUIR r1, c2 -> r3`	`c2 / r1 -> r3 (unsigned divide)`
`Mod r1, r2 -> r3`	`r1 % r2 -> r3`
`ModI r1, c2 -> r3`	`r1 % c2 -> r3`
`ModU r1, r2 -> r3`	`r1 % r2 -> r3 (unsigned modulo)`
`ModUI r1, c2 -> r3`	`r1 % c2 -> r3 (unsigned modulo)`
`Not r1 -> r2`	`~r1 -> r2`
`And r1, r2 -> r3`	`r1 & r2 -> r3`
`AndI r1, c2 -> r3`	`r1 & c2 -> r3`
`Or r1, r2 -> r3`	`r1 | r2 -> r3`
`OrI r1, c2 -> r3`	`r1 | c2 -> r3`

Xor r1, r2 -> r3	r1 ^ r2 -> r3
XorI r1, c2 -> r3	r1 ^ c2 -> r3
Shl r1, r2 -> r3	r1 << r2 -> r3
ShlU r1, r2 -> r3	r1 << r2 -> r3
Shr r1, r2 -> r3	r1 >> r2 -> r3
ShrU r1, r2 -> r3	r1 >> r2 -> r3
Ld r1 -> r2	Deref(r1) -> r2
LdI c1 -> r2	c1 -> r2
LdF c1 -> r2	address of variable slot c1 in stack frame -> r2
LdFA -> r1	address of arguments in stack frame -> r1
LdN -> r1	load uninitialized value into r1
St r1, r2	r1 -> Deref(r2)
StI c1, r2	c1 -> Deref(r2)
Srt r1	r1 -> return value of function
CpyI r1, r2, c3	copy c3 bytes from address r1 to address r2
Jmp b1	b1 -> next block (placeholder if b1 is NULL)

BrE/BrL/BrLE/BrB/BrBE r1, r2, b3, b4	if relation between r1 and r2 is true then
	    b3 -> next block
	else
	    b4 -> next block

BrEI/BrLI/BrLEI/BrBI/BrBEI r1, c2, b3, b4	if relation between r1 and c2 is true then
	    b3 -> next block
	else
	    b4 -> next block

ChE/ChL/ChLE/ChB/ChBE r1, r2, c3, c4 -> r5	if relation between r1 and r2 is true then
	    c3 -> r5
	else
	    c4 -> r5

ChEI/ChLI/ChLEI/ChBI/ChBEI r1, c2, c3, c4 -> r5	if relation between r1 and c2 is true then
	    c3 -> r5
	else
	    c4 -> r5

Call r1, r2, r3, ...	call function r1 with arguments r2, r3, ...
CallV r1, r2, r3, ... -> rx	call function r1 with arguments r2, r3, ... and store return value in rx
CallI c1, r2, r3, ...	call function c1 with arguments r2, r3, ...
CallVI c1, r2, r3, ... -> rx	call function c1 with arguments r2, r3, ... and store return value in rx
Phi r1, r2, r3, ... -> rx	choose between r1, r2, r3, ... and store in rx (stored SEPARATELY from normal operations)
End	last instruction of every function

Operation modes

Each operation may have a number of possible modes. These modes correspond to the types in **BaseType**. For example, `Add<Char> r1, r2 -> r3` assumes that r1, r2 and r3 are Char registers. `Ld<Float> r1 -> r2` assumes that r1 is an IntPtr register and r2 is a Float register. Some operations, such as `Jmp`, `BrX`, `Call` and `CallI` do not have modes. `ChXXX` is an exception – the output register is always Int, and the mode specifies the type of the inputs.

Deref(v1) -> r2

The output r2 is set to the contents at IntPtr v1. The operation mode determines the size of the contents at v1.

Conversion from expressions to intermediate code

In the text below:

- `rx`, `ry`, `rz` mean newly allocated registers.
- "read the value of *x*" or "read from *x*" means to use a register to access *x*, or emit an Ld instruction if x is in indirect storage. *x* may also need to be converted to the type of any operations in which it is used. If *x* is a bit range, emit appropriate shift and mask instructions as well.

Casts for integer, floating-point or pointer types

From type:

- Char: `CvtC`
- Unsigned Char: `CvtUC`
- Short: `CvtS`
- Unsigned Short: `CvtUS`
- Int: `CvtI`
- Unsigned Int: `CvtUI`
- Long: `CvtL`
- Unsigned Long: `CvtUL`
- LongLong: `CvtLL`
- Unsigned LongLong: `CvtULL`
- Float: `CvtF`
- Double: `CvtD`
- IntPtr: `CvtP`

To type:

- (Unsigned) Char: `CvtXXX<Char>`
- (Unsigned) Short: `CvtXXX<Short>`
- (Unsigned) Int: `CvtXXX<Int>`
- (Unsigned) Long: `CvtXXX<Long>`
- (Unsigned) LongLong: `CvtXXX<LongLong>`
- Float: `CvtXXX<Float>`
- Double: `CvtXXX<Double>`
- IntPtr: `CvtXXX<IntPtr>`

Implicit casts

Usual arithmetic conversions

The usual arithmetic conversions attempt to reach a common type for two given expressions.

- If either type is Double, both expressions are converted to Double.
- Otherwise, if either type is Float, both expressions are converted to Float.
- Otherwise, if both expressions have the same type, no conversion is needed.
- Otherwise, if both expressions have signed integer types or both expressions have unsigned integer types, the expression with less precision is converted to the type with greater precision.
- Otherwise, if the unsigned integer type has greater precision than the signed integer type, the signed expression is converted to the unsigned type.

- Otherwise, if the signed integer type can represent all values of the unsigned integer type, the unsigned expression is converted to the signed type.
- Otherwise, both expressions are converted to the unsigned version of the signed type.

Arrays

Except when it is the operand of the `sizeof` operator or the address-of (&) operator, an expression that has type "array of *x*" must be converted to a pointer to *x*.

Sequence points

All pending side effects must be executed at sequence points. These include:

- Function calls, after all arguments have been evaluated.
- The end of the first expression in **AndAndExpression**, **OrOrExpression**, **ConditionalExpression** and **CommaExpression**.
- The end of an initializer.
- The end of a statement.

PrimaryExpression

ID {Id}

Find the ordinary symbol ID in the current **Scope**:

- If it is **TypedefSymbolKind**, raise an error.
- If it is **VariableSymbolKind**, emit LdF slot -> rx, where slot is the slot number of the variable (see VariableSlots in **FunctionScope**).
- If it is **ObjectSymbolKind**, emit `LdI<IntPtr> value -> rx`, where value is an immediate value referencing the linker object for the function or variable. If the object is a function, the resulting type is the function type with one level of indirection (one pointer) and **FunctionDesignator** in RegisterStorageKind is set to True.
- If it is **ConstantSymbolKind**, emit `LdI<Int> value -> rx`, where `value` is the value of the enumeration constant.

Return the new register.

LITERAL_NUMBER {Number}

Refer to the tables below.

Suffix	Decimal constant	Octal or hexadecimal constant

none	`int`
	`long int`
	`long long int`
		`int`
		`unsigned int`
		`long int`
		`unsigned long int`
		`long long int`
		`unsigned long long int`

`u` or `U`	`unsigned int`
	`unsigned long int`
	`unsigned long long int`
		`unsigned int`
		`unsigned long int`
		`unsigned long long int`

`l` or `L`	`long int`
	`long long int`
		`long int`
		`unsigned long int`
		`long long int`
		`unsigned long long int`

Both `u` or `U` and `l` or `L`	`unsigned long int` `unsigned long long int`	`unsigned long int` `unsigned long long int`
`ll` or `LL`	`long long int`	`long long int` `unsigned long long int`
Both `u` or `U` and `ll` or `LL`	`unsigned long long int`	`unsigned long long int`

If a floating-point literal is present, emit LdI<Float> value -> rx if the suffix is f or F. Emit LdI<Double> value -> rx if the suffix is l or L, or if there is no suffix. Return the new register.

LITERAL_CHAR {Char}

If the prefix is L, emit LdI<Short> value -> rx. Otherwise, emit LdI<Char> value -> rx. Return the new register.

LITERAL_STRING {String}

Create a linker object containing the string and emit LdI<IntPtr> value -> rx where value is a reference to the linker object. Return the new register, with type short * if the L prefix is present, or with type char * if no prefix is present.

"(" Expression ")" {Group}

Return the value of the expression.

PrimaryExpression "++" {Increment}

If the type of the expression is not integer or floating-point, raise an error. Otherwise, add an increment operation for the next sequence point.

PrimaryExpression "--" {Decrement}

As above, but schedule a decrement operation for the next sequence point.

PrimaryExpression "(" ")" {Call}

If the type of the expression is not a pointer to a function, raise an error. Otherwise:

- If the function has a return value, emit CallV r1 -> rx where r1 is read from the expression. Return the new register.
- If the function has no return value, emit Call r1. Return **NoStorageKind**.

PrimaryExpression "(" ParameterList ")" {Call2}

As above, but with parameters. For non-register arguments:

- **IndirectStorageKind** arguments must be copied from memory into a sequence of registers. Each register should be an IntPtr. If the value's size is not a multiple of the size of an IntPtr, the last register must be zero-extended to an IntPtr.

PrimaryExpression "[" Expression "]" {Array}

Emit code equivalent to *(expression1 + expression2), but only if one of the expressions has a pointer type and the other has an integer type.

PrimaryExpression "." ID {Member}

If the type of the expression is not a struct type, raise an error. Otherwise:

- If the first expression is **IndirectStorageKind**, emit AddI base, offset -> rx where base is the address of the structure and offset is the byte offset of the field in the structure and return an **IndirectStorageKind** with rx as the Address. If the field spans a number of bits, set BitCount and BitOffset in **IndirectStorageKind**.

PrimaryExpression "->" ID {IndirectMember}

If the type of the expression is not a pointer to a struct type, raise an error. Otherwise, emit AddI base, offset -> rx where base is read from the expression and offset is the byte offset of the field in the structure. Return an **IndirectStorageKind** with rx as the Address. If the field spans a number of bits, set BitCount and BitOffset in **IndirectStorageKind**.

UnaryExpression

"++" CastExpression {Increment}
Emit code equivalent to `expression += 1`.

"--" CastExpression {Decrement}
Emit code equivalent to `expression -= 1`.

"+" CastExpression {Positive}
If the type of the expression is not integer or floating-point, raise an error. Otherwise, return the value of the expression.

"-" CastExpression {Negative}
If the type of the expression is not integer or floating-point, raise an error. Otherwise, emit `SubIR 0, value -> rx` where `value` is read from the expression. Return the new register.

"!" CastExpression {LogicalNot}
If the type of the expression is not integer, floating-point, or a pointer type, raise an error. Otherwise, emit `ChEI value, 0, 1, 0 -> rx` where `value` is read from the expression. Return the new register.

"~" CastExpression {Not}
If the type of the expression is not integer, raise an error. Otherwise, emit `Not value -> rx` where `value` is read from the expression. Return the new register.

"*" CastExpression {Dereference}
If the type of the expression is not a pointer type, raise an error. If the type is a pointer to a function, return the value of the expression with FunctionDesignator set to True. Otherwise, return an **IndirectStorageKind** with `base` as the Address, where `base` is read from the expression.

"&" CastExpression {AddressOf}
If the expression is not an l-value and does not have FunctionDesignator set to True, raise an error. If the expression has FunctionDesignator set to True, return the value of the expression with FunctionDesignator set to False. Otherwise, return a **RegisterStorageKind** with the Address in **IndirectStorageKind** as the Register.

SIZEOF UnaryExpression {SizeOfValue}
If the expression has FunctionDesignator set to True, raise an error. Emit `LdI size -> rx`, where `size` is the size of the type of the expression. Return the new register.

SIZEOF "(" DeclarationSpecifierList ")" {SizeOfType}
Emit `LdI size -> rx`, where `size` is the size of the type. Return the new register.

SIZEOF "(" DeclarationSpecifierList AbstractDeclarator ")" {SizeOfType2}
As above.

CastExpression

"(" DeclarationSpecifierList ")" UnaryExpression {Cast}
See **Casts**.

"(" DeclarationSpecifierList AbstractDeclarator ")" UnaryExpression {Cast2}
As above.

MultiplyExpression

MultiplyExpression "*" CastExpression {Multiply}

If the type of both expressions is not integer or floating-point, raise an error. Emit `Mul value1, value2 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return the new register.

MultiplyExpression "/" CastExpression {Divide}

As above, but emit `Div value1, value2 -> rx` instead.

MultiplyExpression "%" CastExpression {Modulo}

As above, but emit `Mod value1, value2 -> rx` instead.

AddExpression

AddExpression "+" MultiplyExpression {Add}

- If both expressions have integer or floating-point types, emit `Add value1, value2 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return the new register.
- If one expression has a pointer type and the other has an integer type, emit `Mul offset, size ->` rx followed by `Add base, rx -> ry` where `offset` is read from the integer expression, `size` is the size of the type pointed to, and `base` is read from the pointer expression. Return `ry`.
- Otherwise, raise an error.

AddExpression "-" MultiplyExpression {Subtract}

- If both expressions have integer or floating-point types, emit `Sub value1, value2 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return the new register.
- If the first expression has a pointer type and the second expression has an integer type, emit `Mul offset, size ->` rx followed by `Sub base, rx -> ry` where `offset` is read from the integer expression, `size` is the size of the type pointed to, and `base` is read from the pointer expression. Return `ry`.
- If the both expressions have the same type and the type is a pointer type, emit `Sub value1, value2 -> rx` followed by `Div rx, size -> ry` where `value1` is read from the first expression, `value2` is read from the second expression and `size` is the size of the type pointed to. Return `ry`.
- Otherwise, raise an error.

ShiftExpression

ShiftExpression "<<" AddExpression {LeftShift}

If the type of both expressions is not integer, raise an error. Emit `Shl value1, value2 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return the new register.

ShiftExpression ">>" AddExpression {RightShift}

As above, but emit `Shr value1, value2 -> rx` instead.

RelationalExpression

RelationalExpression "<" ShiftExpression {Less}

If both expressions do not have integer, floating-point or compatible pointer types, raise an error. If the common type of the two expressions is:

- An unsigned integer or pointer type, emit `ChB value1, value2, 1, 0 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression, and return `rx`.
- A signed integer or floating-point type, emit `ChL value1, value2, 1, 0 -> rx` and return `rx`.

The type of the returned value must be Int.

Note: Here the definition of "compatible pointer type" does *not* include a pointer to void being compatible with any other kind of pointer.

RelationalExpression "<=" ShiftExpression {LessEqual}

As above, but if the common type of the two expressions is:

- An unsigned integer or pointer type, emit `ChBE value1, value2, 1, 0 -> rx` and return `rx`.
- A signed integer or floating-point type, emit `ChLE value1, value2, 1, 0 -> rx` and return `rx`.

RelationalExpression ">" ShiftExpression {Greater}

As above, but if the common type of the two expressions is:

- An unsigned integer or pointer type, emit `ChBE value1, value2, 0, 1 -> rx` and return `rx`.
- A signed integer or floating-point type, emit `ChLE value1, value2, 0, 1 -> rx` and return `rx`.

RelationalExpression ">=" ShiftExpression {GreaterEqual}

As above, but if the common type of the two expressions is:

- An unsigned integer or pointer type, emit `ChB value1, value2, 0, 1 -> rx` and return `rx`.
- A signed integer or floating-point type, emit `ChL value1, value2, 0, 1 -> rx` and return `rx`.

EqualityExpression

EqualityExpression "==" RelationalExpression {Equal}

- If both expressions have integer, floating-point, or compatible pointer types, emit `ChE value1, value2, 1, 0 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return `rx`.
- If one expression has a pointer type and the other is known to be a null pointer constant, emit `ChEI pointer, 0, 1, 0 -> rx` where `pointer` is read from the pointer expression.

The type of the returned value must be Int.

Note: Unlike with **RelationalExpression**, here the definition of "compatible pointer type" *does* include a pointer to void being compatible with any other kind of pointer.

EqualityExpression “!=” RelationalExpression {NotEqual}

As above, but emit `ChE value1, value2, 0, 1 -> rx` or `ChEI pointer, 0, 0, 1 -> rx` instead.

AndExpression

AndExpression “&” EqualityExpression {And}

If the type of both expressions is not integer, raise an error. Emit `And value1, value2 -> rx` where `value1` is read from the first expression and `value2` is read from the second expression. Return the new register.

XorExpression

XorExpression “^” AndExpression {Xor}

As with **AndExpression**, but emit `Xor value1, value2 -> rx` instead.

OrExpression

OrExpression “|” XorExpression {Or}

As with **AndExpression**, but emit `Or value1, value2 -> rx` instead.

AndAndExpression

AndAndExpression “&&” OrExpression {AndAnd}

If the type of both expressions is not integer, floating-point, or a pointer type, raise an error. Otherwise, emit code equivalent to

```
int temp = 0;

if (value1 != 0)
    temp = value2 != 0;
```

where `value1` is read from the first expression and `value2` is read from the second expression. Return `temp`. See **IfStatement**.

OrOrExpression

OrOrExpression “||” AndAndExpression {OrOr}

If the type of both expressions is not integer, floating-point, or a pointer type, raise an error. Otherwise, emit code equivalent to

```
int temp = 1;

if (value1 == 0)
    temp = value2 != 0;
```

where `value1` is read from the first expression and `value2` is read from the second expression. Return `temp`. See **IfStatement**.

ConditionalExpression

OrOrExpression “?” Expression “:” ConditionalExpression {Conditional}

If the type of the first expression is not integer, floating-point, or a pointer type, raise an error. For the other two expressions, if none the following hold, raise an error:

- Both expressions have the same integer, floating-point, or structure type.
- Both expressions are **NoStorageKind** (i.e. both expressions have void type).
- Both expressions have compatible pointer types.

- One expression has a pointer type and the other type is a pointer to void.
- One expression has a pointer type and the other expression is a null pointer constant.

Emit code equivalent to

```
TYPE temp;

if (value1 != 0)
    temp = value2;
else
    temp = value3;
```

where `TYPE` is the common type derived from the first and second expressions, `value1` is read from the first expression, `value2` is read from the second expression, and `value3` is read from the third expression. Return `temp`. See **IfStatement**.

AssignExpression

ConditionalExpression "=" AssignExpression {Assign}

If none of the following hold, raise an error:

- Both expressions have integer, floating-point or structure types.
- Both expressions have compatible pointer types.
- One expression has a pointer type and the other type is a pointer to void.
- One expression has a pointer type and the other expression is a null pointer constant.

If the storage kind of the first expression is:

- **IndirectStorageKind** and the type of the second expression is **RegisterStorageKind**, emit `St right, left` where `right` is read from the second expression and `left` is the Address of the first expression. Return the value read from the second expression.
- **IndirectStorageKind** and the type of the second expression is **IndirectStorageKind**, emit `CpyI right, left, size` where `right` is the Address of the second expression, `left` is the Address of the first expression, and `size` is the size of the first expression's type. Return the value of the second expression.

If the first expression refers to a bit range, emit appropriate bitwise instructions to calculate the resulting value.

ConditionalExpression "+=" AssignExpression {Add}

Emit code equivalent to

```
left1 = left2 + right
```

where `left1` is the l-value of the first expression, `left2` is read from the first expression and `right` is read from the second expression. See **AddExpression** for type restrictions.

ConditionalExpression "-=" AssignExpression {Subtract}

As above, but emit code equivalent to

```
left1 = left2 - right
```

ConditionalExpression "*=" AssignExpression {Multiply}

As with "Add", but emit code equivalent to

```
left1 = left2 * right
```

ConditionalExpression "/=" AssignExpression {Divide}
As with “Add”, but emit code equivalent to

```
left1 = left2 / right
```

ConditionalExpression "%=" AssignExpression {Modulo}
As with “Add”, but emit code equivalent to

```
left1 = left2 % right
```

ConditionalExpression "&=" AssignExpression {And}
As with “Add”, but emit code equivalent to

```
left1 = left2 & right
```

ConditionalExpression "|=" AssignExpression {Or}
As with “Add”, but emit code equivalent to

```
left1 = left2 | right
```

ConditionalExpression "^=" AssignExpression {Xor}
As with “Add”, but emit code equivalent to

```
left1 = left2 ^ right
```

ConditionalExpression "<<=" AssignExpression {LeftShift}
As with “Add”, but emit code equivalent to

```
left1 = left2 << right
```

ConditionalExpression ">>=" AssignExpression {RightShift}
As with “Add”, but emit code equivalent to

```
left1 = left2 >> right
```

CommaExpression

CommaExpression "," AssignExpression {Comma}
Emit code to evaluate the first expression, followed by code to evaluate the second expression. Return the value of the second expression.

Conversion from statements to intermediate code

LabeledStatement

ID ":" Statement {Id}

If the label is already defined, raise an error. Emit `Jmp newBlk` where `newBlk` becomes the new current block. Add the block to Labels in the current **FunctionScope**. If there are PendingGotos for this label, for each pending block adjust the `Jmp` operation in the block.

CASE ConditionalExpression ":" Statement {Case}

Find the nearest **ControlScope** with the Switch keyword. If there is none, or the case is already defined, raise an error. Emit `Jmp newBlk` where `newBlk` becomes the new current block. Add the block to Cases in the **ControlScope**.

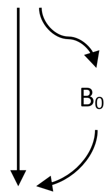
DEFAULT ":" Statement {Default}

As above, but instead of adding the block to Cases, set DefaultCase in the **ControlScope**.

IfStatement

IF "(" Expression ")" Statement {If}

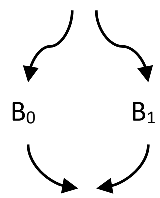
If the type of the expression is not integer, floating-point or a pointer type, raise an error. Emit `BrEI value, 0, nextBlk, nonZeroBlk` where:



- `nextBlk` is a new block that becomes the new current block after the **IfStatement**.
- `value` is read from the expression.
- `nonZeroBlk` is a new block in which the statement is executed. Emit `Jmp nextBlk` as the last instruction in the block.

IF "(" Expression ")" Statement ELSE Statement {IfElse}

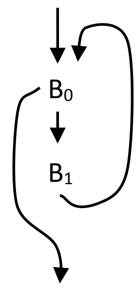
If the type of the expression is not integer, floating-point or a pointer type, raise an error. Emit `BrEI value, 0, zeroBlk, nonZeroBlk` where:



- `nextBlk` is a new block that becomes the new current block after the **IfStatement**.
- `value` is read from the expression.
- `zeroBlk` is a new block in which the second statement is executed. Emit `Jmp nextBlk` as the last instruction in the block.
- `nonZeroBlk` is a new block in which the first statement is executed. Emit `Jmp nextBlk` as the last instruction in the block.

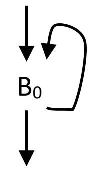
WhileStatement: WHILE "(" Expression ")" Statement

If the type of the expression is not integer, floating-point or a pointer type, raise an error. Emit `Jmp testBlk` and create a new **ControlScope** where:



- The **ControlScope** has BreakTarget = `nextBlk` and ContinueTarget = `testBlk`.
- `nextBlk` is a new block that becomes the new current block after the **WhileStatement**.
- `testBlk` is a new block created by emitting `BrEI value, 0, nextBlk, bodyBlk`.
- `value` is read from the expression.
- `bodyBlk` is a new block in which the statement is executed. Emit `Jmp testBlk` as the last instruction in the block.

DoWhileStatement: DO Statement WHILE “(“ Expression “)” “;”



If the type of the expression is not integer, floating-point or a pointer type, raise an error. Emit `Jmp bodyBlk` and create a new **ControlScope** where:

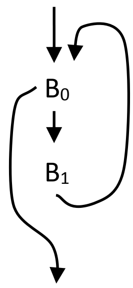
- The **ControlScope** has BreakTarget = `nextBlk` and ContinueTarget = `bodyBlk`.
- `nextBlk` is a new block that becomes the new current block after the **DoWhileStatement**.
- `bodyBlk` is a new block in which the statement is executed. Emit `BrEI value, 0, nextBlk, bodyBlk` as the last instruction in the block.
- `value` is read from the expression.

ForStatement

FOR “(“ ExpressionStatement ExpressionStatement “)” Statement {NoIterate}

As below, except with no third expression to evaluate.

FOR “(“ ExpressionStatement ExpressionStatement Expression “)” Statement {Iterate}

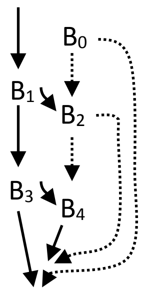


If the type of the second expression is not integer, floating-point or a pointer type, raise an error. Emit code to evaluate the first expression, emit `Jmp testBlk`, and create a new **ControlScope** where:

- The **ControlScope** has BreakTarget = `nextBlk` and ContinueTarget = `testBlk`.
- `nextBlk` is a new block that becomes the new current block after the **ForStatement**. `testBlk` is a new block created by emitting `BrEI value, 0, nextBlk, bodyBlk`.
- `value` is read from the second expression.
- `bodyBlk` is a new block in which the statement is executed. Then emit code to evaluate the third expression (if present), and emit `Jmp testBlk` as the last instruction in the block.

In the diagram, B_0 is `testBlk` and B_1 is `bodyBlk`. The **ForStatement** is very similar to the WhileStatement, the only differences being the addition of the first expression and the third expression.

SwitchStatement: SWITCH “(“ Expression “)” Statement



If the type of the expression is not integer, raise an error. Emit code to evaluate the expression, create a new **ControlScope**, execute the statement in an isolated block `stmtBlk`, and then for each case in the **ControlScope**, emit `BrEI value, case, caseBlk, testBlk` where:

- The **ControlScope** has BreakTarget = `nextBlk`.
- `stmtBlk` is a new block in which the statement is executed. Emit `Jmp nextBlk` as the last instruction in the block.
- `nextBlk` is a new block that becomes the new current block after the **SwitchStatement**.
- `value` is read from the expression (this should be done only once, in the block for the first case).
- `case` is the test value of the case.
- `caseBlk` is the block associated with the case (inside `stmtBlk`).
- `testBlk` is a new block for the test code for the next case (`BrEI ...`). If there are no more cases and there is a default case, the default case must be used in `BrEI` as the branch target instead of `testBlk`. If there is no default case, `nextBlk` must be used as the branch target.

If there are no cases defined and there is a default case, emit `Jmp dfltBlk` where `dfltBlk` is the default case block. If there is no default case, emit `Jmp nextBlk`.

In the diagram, B_0, B_2, B_4 are within `stmtBlk`. B_1 and B_3 are the case test blocks. Note that B_0 does not necessarily have a predecessor, as in the following example:

```
int a, b;
...
switch (...)
{
    b = a + 2; // B0
case 1:        // B2
    ...
case 2:        // B4
    ...
}
```

ContinueStatement: CONTINUE ";"

Find the nearest **ControlScope** with a defined ContinueTarget. If there is none, raise an error. Otherwise, emit `Jmp ContinueTarget`. Create a new block and set it as the current block.

> Note the importance of creating a new block after the `Jmp` operation. Consider the following code.

```
do
{
    ...
    if (...)
        continue;
    ...
} while (...);
```

> The **IfStatement** is converted by creating a new block for the sub-statement, executing that sub-statement, and finally emitting a `Jmp` to the following block. This works even though the sub-statement logically ends with a jump:

```
bodyBlk:
    ...
    BrEI value, 0, nextBlk, nonZeroBlk
nonZeroBlk: // sub-statement
    Jmp bodyBlk // "continue;"
newBlk: // created by ContinueStatement
    Jmp nextBlk // created by IfStatement
nextBlk:
    ...
```

> `newBlk` is created by the **ContinueStatement** even though it is never used. This scheme enables greater consistency and does not lead to bigger code because dead code elimination will delete `newBlk` since it is unused.

BreakStatement: BREAK ";"

Find the nearest **ControlScope** with a defined BreakTarget. If there is none, raise an error. Otherwise, emit `Jmp BreakTarget`. Create a new block and set it as the current block.

ReturnStatement

RETURN ";" {NoValue}

Emit `Jmp end` where `end` is the EndBlock in the current **FunctionScope**.

RETURN Expression ";" {Value}

If the function does not have a return value, raise an error. Otherwise, update the Value of the variable with ID ReturnVariableId (from the current **FunctionScope**) to point to the value of the expression. Emit `Jmp end` where `end` is the EndBlock in the current **FunctionScope**.

GotoStatement: GOTO ID ";"

If the label is defined in the current **FunctionScope**, Emit `Jmp target` where `target` is the label target. Otherwise, emit `Jmp NULL` and add the current block to the PendingGotos in the current **FunctionScope**. Create a new block and set it as the current block.

Declaration

For each variable, add it to the current **Scope**, allocate a stack frame slot and emit `LdF slot -> rx`.

Initializers are then processed in order.

ExpressionStatement

";" {Empty}

No action is performed.

Expression ";" {NonEmpty}

Emit code to evaluate the expression.

Block

"{" "}" {Empty}

No action is performed.

"{" StatementList "}" {NonEmpty}

Emit code to execute each statement in the statement list.

Functions

Arguments

Arguments are passed to functions in the `Call`/`CallV`/`CallI`/`CallVI` operations. These arguments are then logically stored in memory and accessible to the callee through the `LdFA` operation. When the name of an argument is first used, the address of the argument is loaded and an **IndirectStorageKind** variable is added to ParameterMap in the current **FunctionScope**.

Structure return values

When a function returns a structure that is larger than 8 bytes, an extra parameter is inserted at the beginning of the parameter list. This parameter is a pointer to the return value, allocated by all callers before calling the function.

Optimizations

Constant propagation

Constant propagation is performed using a variant of "conditional constant propagation". In this algorithm, every register is described using a predicate of one of the following forms:

- $\bot$
- $\top$
- $x = c$
- $x > c$
- $x < d$
- $x > c \wedge x < d$

If necessary, the algorithm can easily be expanded to allow arbitrary predicate forms. The standard laws of Boolean algebra apply, including:

- $\bot \wedge p \to \bot$
- $\bot \vee p \to p$
- $\top \wedge p \to p$
- $\top \vee p \to \top$
- $x > c_1 \wedge x > c_2 \to x > \max(c_1, c_2)$
- $x > c_1 \vee x > c_2 \to x > \min(c_1, c_2)$
- $x < c_1 \wedge x < c_2 \to x < \min(c_1, c_2)$
- $x < c_1 \vee x < c_2 \to x < \max(c_1, c_2)$

Every block contains a lookup table mapping each register to a predicate. There is also a work queue containing the blocks that need to be processed by the algorithm. The algorithm begins with the start block in the work queue. For example:

```
Start:
       LdI 1 -> r1
       BrLI r1, 2, Block1, Block2
Block1:
       LdI 2 -> r2
       Jmp Common
Block2:
       LdI 3 -> r3
       Jmp Common
Common:
       Φ(r2,r3) -> r4
```

The algorithm begins by associating every register with $\bot$ in the `Start` block:

Table for `Start`	r_1	r_2	r_3	r_4
	$\bot$	$\bot$	$\bot$	$\bot$

By the end of the first pass:

Table for `Start`	r_1	r_2	r_3	r_4
	$x = 1$	$\bot$	$\bot$	$\bot$

At the `BrLI` operation, the algorithm computes $r_1: x = 1 \wedge x < 2 \to x = 1$ for the positive branch and records this in the table for `Block1` (along with the other inherited values) while adding `Block1` to the work queue. It also computes $r_1 : x = 1 \wedge x \geq 2 \rightarrow \perp$ for the negative branch, but does not add `Block2` to the work queue; execution cannot reach Block2 since the truth value computed is ⊥. By the end of the second pass:

Table for `Block1`	r_1	r_2	r_3	r_4
	$x = 1$	$x = 2$	$\perp$	$\perp$

Due to the `Jmp` operation, `Common` has been added to the work queue. In the third pass, the algorithm computes $r_4 : r_2 \vee r_3 \rightarrow x = 2 \vee \perp \rightarrow x = 2$. By the end of the third pass:

Table for `Common`	r_1	r_2	r_3	r_4
	$x = 1$	$x = 2$	$\perp$	$x = 2$

For this example, the algorithm terminates here.

Algorithm outline

The algorithm must also account for cycles in the control flow graph (CFG); these occur naturally when there are loops. An outline of the algorithm is presented below.

```
for every block B:
	B.LastIteration starts as 0
	B.Table starts as {}
	B.PredTable starts as {}
	B.VisitCount starts as 0

WorkQueue = { B0 } // start block
Iteration = 1
while WorkQueue ≠ {}:
	remove block B from WorkQueue
	Process(B)
rewrite all operations with constant values
algorithm terminates

Process(B):
	Restarted = False
	if B.LastIteration = Iteration:
		Iteration = Iteration + 1 // cycle detected; restart in new iteration
		Restarted = True
		WorkQueue = {}
	OldTable = B.Table
	for each (R, V) in B.PredTable:
		if R ∈ B.Table:
			B.Table[R] = B.Table[R] ∧ V
	B.PredTable = {}
	ChangeList = {}
	for each operation P in B that defines a register (including Φ operations):
		assume P defines register R
		V = compute new predicate for P taking into consideration B.VisitCount
		B.Table[R] = V
		if (R ∉ OldTable and V ≠ ⊥) or (R ∈ OldTable and V ≠ OldTable[R]):
			add R to ChangeList
	if (ChangeList ≠ {}) or Restarted:
		examine the Jmp/Br that ends B to determine reachable successors
		for each reachable successor S of B:
			if S.LastIteration = Iteration:
				for each R in ChangeList:
					S.Table[R] = S.Table[R] ∨ B.Table[R]
			else:
				S.Table = B.Table // inherit value table
			if B ends with a Br operation with a computable predicate:
				// "computable predicate" means the second operand is
				// effectively constant
				assume R is the first operand in the Br operation
				assume V is the effective predicate for the Br operation
				if S is the negative branch:
					V = ¬V
				if R ∈ S.PredTable:
					S.PredTable[R] = S.PredTable[R] ∨ V
				else:
					S.PredTable[R] = V
			add S to WorkQueue
	B.LastIteration = Iteration
	B.VisitCount = B.VisitCount + 1
```

The algorithm could be improved by storing the register-to-predicate table in a global variable instead of a variable local to each block.

Interpretation of top and bottom (tautology and contradiction)

At the end of the algorithm, every register should be associated with a predicate. If a register's predicate is T, the algorithm has essentially "given up" on tracking the register's possible values (see below) – the register's value is completely unknown. If a register's predicate is ⊥, the register has no value, either because its definition depends on uninitialized values or because its definition occurs in an unreachable block.

Computing new predicates for operations

The constant propagation algorithm effectively “executes” the intermediate code while determining possible values for each register. Loops in the code create cycles in the CFG, and these are handled in the algorithm by discarding results from previous “iterations”. Without a pre-determined number of iterations to run through, the algorithm is not guaranteed to terminate. Therefore, the VisitCount variable holds an integer indicating the number of times a block has been processed. If the count exceeds a set threshold, the predicate computation functions below must begin to return $\top$, eventually causing the algorithm to halt. Any constant propagation algorithm that did not require such a halting mechanism would effectively solve the halting problem.

Examples of predicate computation functions

- $p \rightarrow p$
- $p{+}\bot{\rightarrow}\bot$ and same with all other operators
- $p + \top \rightarrow \top$
- $p + 0 \rightarrow p$ and $p - 0 \rightarrow p$
- $[x > c] + [x = d] \rightarrow [x > c + d]$
- $p \times 0 \rightarrow 0$
- $p \times 1 \rightarrow p$
- $[x > c] \div 2 \rightarrow [x > \mathrm{Floor}(\frac{c}{2})]$
- $\mathrm{And}(p, 0) \rightarrow 0$
- $\mathrm{Or}(p, 0) \rightarrow p$

Example

Consider the following C code fragment:

```
int a = 0;
int i = 0;

for (i = 0; i < 10; i++)
{
    a++;
}

i += 10;
```

This may translate to:

```
Start:
       LdI 0 -> r1
       LdI 0 -> r2
       Jmp Test
Test:
       Φ(r1,r3) -> r4
       Φ(r2,r5) -> r6
       BrLI r6, 10, Body, Next
Body:
       AddI r4, 1 -> r3
       AddI r6, 1 -> r5
       Jmp Test
Next:
       AddI r6, 10 -> r7
```

The constant propagation algorithm would run as follows, assuming that the threshold for VisitCount is 1:

Register	r_1	r_2	r_3	r_4	r_5	r_6	r_7
	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
`Start`	$x = 0$	$x = 0$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
`Test`	$x = 0$	$x = 0$	$\bot$	$x = 0$	$\bot$	$x = 0$	$\bot$
`Body`	$x = 0$	$x = 0$	$x = 1$	$x = 0$	$x = 1$	$x = 0$	$\bot$
`Test`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x = 1$	$\top$	$\bot$
`Body`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x = 1$	$x < 10$	$\bot$
	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 10$	$\bot$
`Test`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 11$	$\bot$
`Body`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 10$	$\bot$
	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 11$	$\bot$
`Test`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 11$	$\bot$
`Body`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 10$	$\bot$
	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x < 11$	$\bot$
`Next`	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x = 10$	$\bot$
	$x = 0$	$x = 0$	$x = 1$	$\top$	$x < 11$	$x = 10$	$x = 20$

Store forwarding

Definitions

BaseType

These are the basic types:

- Char (integer type)
- Short (integer type)
- Int (integer type)
- Long (integer type)
- LongLong (integer type)
- Float (floating-point type)
- Double (floating-point type)
- IntPtr (pointer type) – only for intermediate code; must not be used as an actual type (e.g. in **Type**)
- Void (void type) – only for the type system; must not be used for intermediate code

Block

- PhiOperations : List of ϕ operations
- Operations : List of intermediate code operations

When a block is created, it must be added to "Blocks" in the current **FunctionScope**.

ControlKeyword

- While
- DoWhile
- For
- Switch

ControlScope

- Parent : ControlScope
- Keyword : ControlKeyword
- BreakTarget : Block (optional)
- ContinueTarget : Block (optional)
- Cases : Map from LongLong to Block
- DefaultCase : Block (optional)

EnumField

- Name : String
- Value : Int

EnumType

- Tag : String
- Fields : List of EnumField

FunctionScope

- StartBlock : Block
- EndBlock : Block
- Blocks : Set of Block
- BlockMap : Map from Integer to Block

- Slots : Map from Integer to FrameSlot
- Variables : Map from VariableId to FunctionVariable
- SlotCache : Map from Integer to Register
- ReturnVariableId : VariableId
- ParameterMap : Map from Int to VariableId
- Labels : Map from String to Block
- PendingGotos : Multimap from String to Block

If the function has a return value, ReturnVariableId contains the ID of the “return variable”, which stores the return value. This variable must be added to the StartBlock before conversion begins. When conversion of the function’s statements has finished and ϕ operations have been inserted into EndBlock, a `Srt` operation is emitted as the second last instruction in EndBlock.

FunctionType

- ReturnType : Type
- Variadic : Bool
- Parameters : List of Type

FunctionVariable

- Parameter : Bool
- Index : Int
- AddressRegister : Register
- Type : Type

FrameSlot

- Size : Int
- VariableId : VariableId

ImmediateValue

- Type : BaseType
- Value : <type specified in BaseType>
- IsReference : Bool
- Reference : ObjectReference
- ReferenceOffset : Int

This structure describes a value used for literal values and immediate operands. If IsReference is True, Reference contains the ID of a linker object and ReferenceOffset contains the number of bytes to add to the address of the linker object. Type must be IntPtr.

ObjectReference

An integer ID for a linker data object – e.g. global variable or function.

OrdinarySymbol

All sub-types

- Name : String

VariableSymbolKind

- Id : VariableId

Id specifies a unique identifier for a variable. Since names can shadow names from an outer scope, Id distinguishes between two variables with the same name.

ObjectSymbolKind

- Type : Type
- Reference : ObjectReference

This type is used for functions, global variables and static local variables.

TypedefSymbolKind

- Target : Type

ConstantSymbolKind

- Value : Int

Register

An integer ID for a register.

Scope

- Parent : Scope
- Symbols : Map from String to OrdinarySymbol
- Tags : Map from String to TagSymbol

This structure represents a lexical scope. It is only used during conversion to intermediate code in order to keep track of visible names. Labels are not included here because they have function-level scope and can only be resolved in a separate pass.

Storage

RegisterStorageKind

- Register : Register
- FunctionDesignator : Bool
- BitCount : Int
- BitOffset : Int

Register storage can never act as an l-value.

IndirectStorageKind

- Address : Register
- LValue : Bool
- BitCount : Int
- BitOffset : Int

Indirect storage sometimes cannot act as an l-value (e.g. a struct returned from a function).

NoStorageKind

This represents no value, i.e. “void”.

StructField

- Name : String
- Type : Type
- Bits : Int

StructType

- Keyword : TypeKeyword
- Tag : String

- Fields : List of StructField

TagSymbol

- Name : String
- Type : Type

Any usage of a tag must be checked against the keyword with which it was originally defined. An error must be raised if there is a mismatch.

Type

All sub-types

- Traits : TypeTraits

BaseTypeKind

- Base : BaseType
- EnumTag : String (optional)

Enumeration types are treated identically to Int types, but the enumeration tag is stored in EnumTag.

PointerTypeKind

- Child : Type (optional)

If Child is not specified, the type is a void pointer.

ArrayTypeKind

- Size : IntPtr (optional)
- Child : Type

If Size is not specified, an error must be raised when the size of the type is being calculated. The type then behaves identically to **PointerTypeKind** with the same Child.

StructTypeKind

- Struct : StructType

EnumTypeKind

- Enum : EnumType

This type is not used for definitions. It is only used for **TagSymbol** instances.

IncompleteTypeKind

- Keyword : TypeKeyword
- Tag : String

Incomplete type specifications must be treated identically to struct type specifications if the struct is fully defined at a later point. For example, in

```
typedef struct my_struct other_type_name;
other_type_name *a;
struct my_struct { int b; };
```

the variable “a” must be treated as a pointer to a full instance of `my_struct`.

FunctionTypeKind

- Function : FunctionType

TypeKeyword

These correspond to the types which have “tags”.

- Struct
- Union
- Enum

TypeTraits (flags)

- Signed (applies only to basic types Char, Short, Int, Long, LongLong)
- Unsigned (applies only to certain types as with Signed)
- Volatile
- Const

TypedValue

- Type : Type
- Value : Storage

This structure describes a storage location along with a type. **TypedValues** are the result of expressions, and operators use them as input and for type checking.

VariableId

An integer ID for a variable, preferably a 64-bit value. This is necessary to distinguish between different instances of variables with the same name (e.g. “i” in an outer scope and “i” in an inner scope).