Applied Static Analysis

Why Static Analysis?

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Questions that we may ask about a program:

- Will the variable `x` always contain the same value?
- Which objects can variable `x` points to?
- What is a lower/upper bound on the value of the integer variable `x`?
- Which methods are called by a method invocation?
- How much memory is required to execute the program?
- Will it throw a `NullPointerException`?
- Will it leak sensitive data? Will data from component `a` flow to component `b`?

Buggy C-Program:

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int main(int argc, const char * argv[]) {
    char *p, *q;
    p = NULL;
    printf("%s",p);
    q = (char *)malloc(100);
    p = q;
    free(q);
    *p = 'x';
    free(p);
    p = (char *)malloc(100);
    q = (char *)malloc(100);
    q = p;
    strcat(p,q);
}
```

What is Static Analysis?

A static analysis of a program is a *sound*, *finite*, and *approximate* calculation of the program's execution semantics which helps us to solve practical problems.

Purposes of Code Analyses

- Finding code smells.
- Quality assessments.
- Improving the quality of the code.
- Support debugging of code.
- Optimizing the code.

Not every analysis which does not execute the code is a *static analysis*!

Finding Programming Bugs

```
class X {
    private long scale;
    X(long scale) { this.scale = scale; }
    void adapt(BigDecimal d){
        d.setScale(this.scale);
    }
}
```

There is typically more than one way to find certain bugs and not all require (sophisticated) static analyses!

Finding Bugs Using Bug Patterns

```
import org.opalj.br._
import org.opalj.br.instructions.{INVOKEVIRTUAL,POP}
val p = analyses.Project(org.opalj.bytecode.JRELibraryFolder) // <= analyze the JRE
p.allMethodsWithBody.foreach{m =>
  m.body.get.collectPair{
    case (
        i @ INVOKEVIRTUAL(ObjectType("java/math/BigDecimal"),"setScale",_),
        POP
    ) => i
  }
  .foreach(i => println(m.toJava(i.toString)))
}
```

Real instance in Java 8u191:
com.sun.rowset.CachedRowSetImpl.updateObject(int,Object,int)

Finding Bugs Using Bug Patterns (Assessment)

- Advantages:
  - very fast and scale well to very large programs
  - (usually) simple to implement
- Disadvantages:
  - typically highly specialized to specific language constructs and APIs
  - requires some understanding how the issue typically manifests itself in the (binary) code
  - small variations in the code may escape the anaylsis
  - to cover a broader range of similar issues significant effort is necessary

Finding Bugs Using Machine Learning

Finding Bugs Using Machine Learning

Guess the problem of the following JavaScript code snippet:

```
function setPoint(x, y) { ... } // <= given

var x_dim = 23;
var y_dim = 5;
setPoint(y_dim, x_dim);
```

Finding Bugs Using Machine Learning (Assessment)

- Finds bugs that are practically impossible to find using other approaches; hence, often complementary to classic static analyses and also bug pattern based analyses.
- Requires the analysis of a huge code base; it may be hard to find enough code examples for less frequently used APIs.

Finding Bugs by Mining Usage Patterns (Idea)

Is the following code buggy?

```
Iterator<?> it = ...
it.next();
while (it.hasNext()) {
    it.next();
    ...
}
```

Finding Bugs Using Generic Static Code Analysis

```
class com.sun.imageio.plugins.png.PNGMetadata{
    void mergeStandardTree(org.w3c.dom.Node) {
        [...]
        if (maxBits > 4 || maxBits < 8) {
            maxBits = 8;
        }
        if (maxBits > 8) {
            maxBits = 16;
        }
        [...]
    }
}
```

Finding Bugs Using Generic Static Code Analysis

```
class sun.font.StandardGlyphVector {
    private int[] glyphs; // always
    public int getGlyphCharIndex(int ix) {
        if (ix < 0 && ix >= glyphs.length) {
            throw new IndexOutOfBoundsException("" + ix);
        }
    }
}
```

Finding Bugs Using Generic Static Code Analysis

```
class sun.tracing.MultiplexProviderFactory {
    public void uncheckedTrigger(Object[] args) {
        […]
        Method m = Probe.class.getMethod(
            "trigger",
            Class.forName("[java.lang.Object")
        );
        m.invoke(p, args);
    }
}
```

Finding Bugs Using Generic Static Code Analysis

```
package com.sun.corba.se.impl.naming.pcosnaming;
class NamingContextImpl {
    public static String nameToString(NameComponent[] name)
        [...]
        if (name != null || name.length > 0) {
            [...]
        }
        [...]
    }
}
```

Finding Bugs Using Static Code Analysis ?

```
private boolean ...isConsistent(
        String alg,
        String exemptionMechanism,
        Hashtable<String, Vector<String>> processedPermissions) {
    String thisExemptionMechanism =
        exemptionMechanism == null ? "none" : exemptionMechanism;
    if (processedPermissions == null) {
        processedPermissions = new Hashtable<String, Vector<String>>();
        Vector<String> exemptionMechanisms = new Vector<>(1);
        exemptionMechanisms.addElement(thisExemptionMechanism);
        processedPermissions.put(alg, exemptionMechanisms);
        return true;
    }
    [...]
}
```

Finding Bugs Using (Highly) Specialized Static Analyses

Do you see the security issue?

```
Cipher c = Cipher.getInstance("DES/CBC/PKCS5PADDING")
```

(True|False) (Positives|Negatives)

- a true positive is the correct finding (of something relevant)
- a false positive is a finding that is incorrect (i.e., which can't be observed at runtime)
- a true negative is the correct finding of no issue.
- a false negative refers to those issues that are not reported.

Unguarded Access - True Positive ?

```
void printIt(String args[]) {
    if (args != null) {
        System.out.println("number of elements: " + args.length);
    }
    for (String arg : args) {
        System.out.println(arg);
    }
}
```

Implicitly Guarded Access

```
void printReverse(String args[]) {
    int argscount = 0;
    if (args != null) {
        argscount = args.length;
    }
    for (int i = argscount - 1; i >= 0; i--) {
        System.out.println(args[i]);
    }
}
```

Irrelevant True Positives

Let's assume that the following function is only called with `non-null` parameters.

```
private boolean isSmallEnough(Object i) {
    assert(i != null);
    Object o = " "+i;
    return o.length < 10;
}
```

Complex True Positives

The cast in line 5 will fail:

```
GeneralPath result = new GeneralPath(GeneralPath.WIND_NON_ZERO);
[…]
if (dx != 0 || dy != 0) {
    AffineTransform tx = AffineTransform.getTranslateInstance(dx, dy);
    result = (GeneralPath)tx.createTransformedShape(result);
}
```

Complex True Positives - Assessment

The sad reality:

[…] the general trend holds; a not-understood bug report is commonly labeled a false positive, rather than spurring the programmer to delve deeper. The result? We have completely abandoned some analyses that might generate difficult to understand reports. [^FindBugsInTheRealWorld]

Soundiness

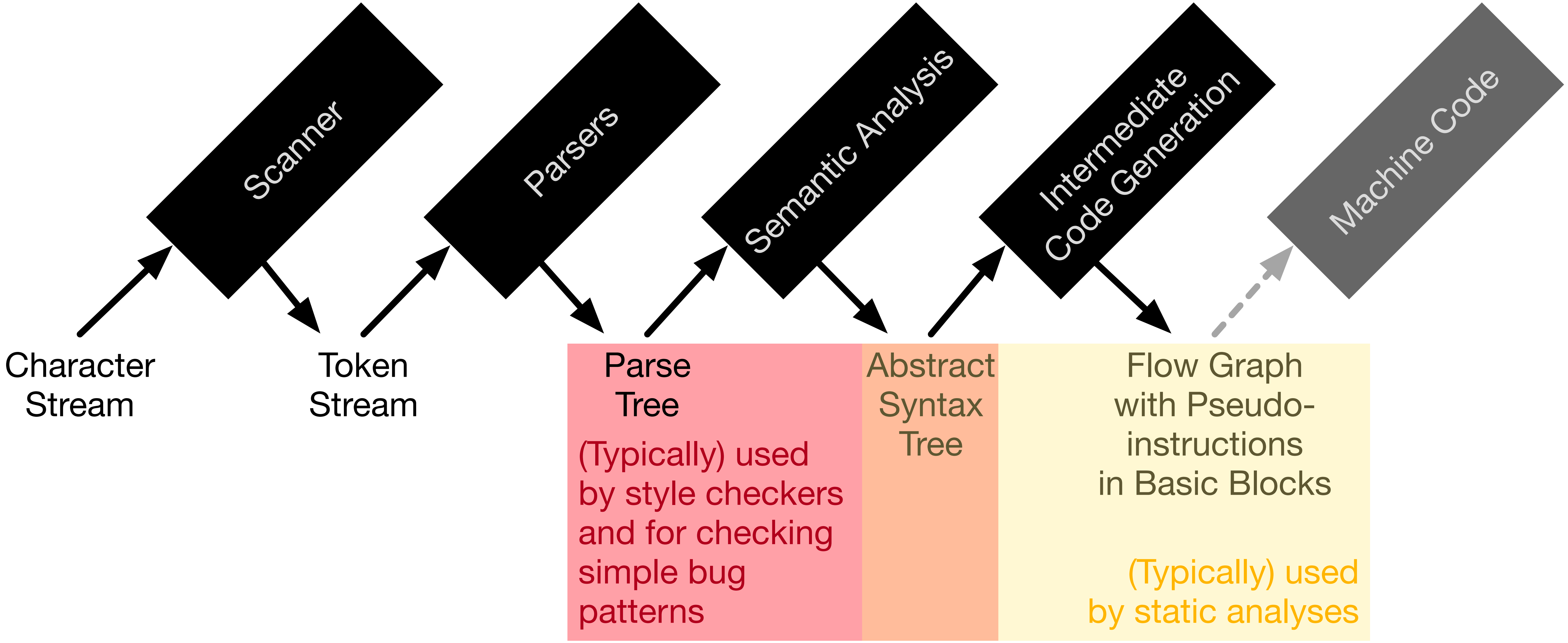
[…] in practice, soundness is commonly eschewed: we [the authors] are not aware of a single realistic whole-programa analysis tool […] that does not purposely make unsound choices.
[…]
Soundness is not even necessary for most modern analysis applications, however, as many clients can tolerate unsoundness. [^Soundiness]

Soundiness - Java

Common features that are often not soundly handled in Java:

1. Intents (in Android Programs)
2. Reflection (*often mentioned in research papers*)
3. Native methods (*often mentioned in research papers*)
4. Dynamic Class Loading / Class Loaders (*sometimes mentioned in research papers*)
5. (De)Serialization (*often not considered at all*)
6. Special System Hooks (e.g., `shutdownHooks`) (*often not considered at all*)
7. "Newer" language features

The Relation between Compilers and Static Analyses



The Relation between Compilers and Static Analyses

Source Code:

```
i = j + 1;
```

Tokens:

```
Ident(i) WS Assign WS Ident(j) WS Operator(+) WS Const(1) Semicolon
```

AST with (type) annotations:

```
AssignmentStatement(
    target     = Var(name=i,type=Int),
    expression = AddExpression(
                     type  = Int,
                     left  = Var(name=j,type=Int),
                     right = Const(1)))
```

(Classical) Compiler Optimizations

- common subexpression elimination
- constant folding and propagation
- loop fusion
- loop invariant code motion
- code-block reordering
- dead-code elimination
- …

often rely on the identification of the so-called *control dependencies* which are computed using control-flow graphs (CFGs). Though the optimizations as such are already relevant (e.g., to help deobfuscate code), the underlying techniques, such as, loop identification or live-variable analyses are also relevant for static analyses on their own.

(Control-)Flow Graph (CFG)

Given a labeled, directed control-flow graph $G = (N, E, n_o)$ consiting of the finite set N of the statements of the program and the set of edges E which represent the control flow between statements.

- N is partitioned into two subsets:
  - N^S – *statement nodes* with at most one successor and
  - N^P – *branch nodes* with at least two *distinct* successors
- $N^E \subseteq N^S$ denotes the nodes in N^S that have no successors (the exit nodes)
- the start node n_0 has no incoming edges and all nodes in N are reachable.
- if N^E contains only one element and this element is reachable from all other nodes of G then G satisfies the *unique end node property*

CFG - Nodes

```
public static long sumOfInts(int upTo) {
    long s = 1l;            // stmt node (assign)
    int i = 2;              // stmt node (assign)
    while (i < upTo) {      // branch node (if)
        s += i;             // stmt node (add followed by assign)
        i++;                // stmt node (inc)
    } // goto loop start - stmt node; control-transfer instruction
    return s;               // stmt node
}
```

CFGs - Paths

A CFG path $\boldsymbol{\pi}$ from $\boldsymbol{n_i}$ to $\boldsymbol{n_k}$ is a sequence of nodes $\boldsymbol{n_i, n_{i+1}, \ldots, n_k}$ such that for each consecutive pair $\boldsymbol{(n_i, n_j)}$ in the path an edge from $\boldsymbol{n_i}$ to $\boldsymbol{n_j}$ exists.

A path is *nontrivial* if it contains at least two nodes.

A path is *maximal* if it is infinite or terminates in an end node.

Dominance

A Node $\boldsymbol{n}$ dominates node $\boldsymbol{m}$ in $\boldsymbol{G}$ (dom(n,m)) if *every* path from the start node $\boldsymbol{n_0}$ to $\boldsymbol{m}$ passes through $\boldsymbol{n}$ (hence, dom is reflexive).

Dominance - Example

```
public static int abs(int i) {
    if(i == Integer.MIN_VALUE)
        throw new ArithmeticException();
    if(i < 0)
        i = -i;
    return i;
}
```

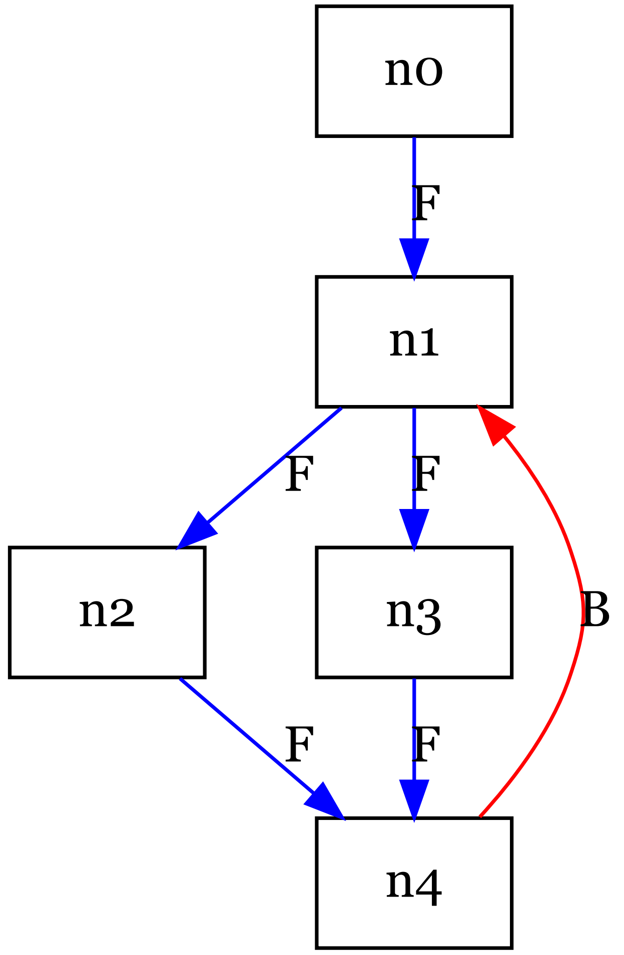
(Ir)Reducible CFGs

A CFG $G = (N, E, n0)$ is reducible if ...

- E can be partitioned into disjoint sets E_f (forward edges) and E_b (backward edges)
- such that (N, E_f) forms a directed-acyclic graph (DAG) in which each node can be reached from the start node n_0
- and for all edges $e \in E_b$, the target of e dominates the source of e.

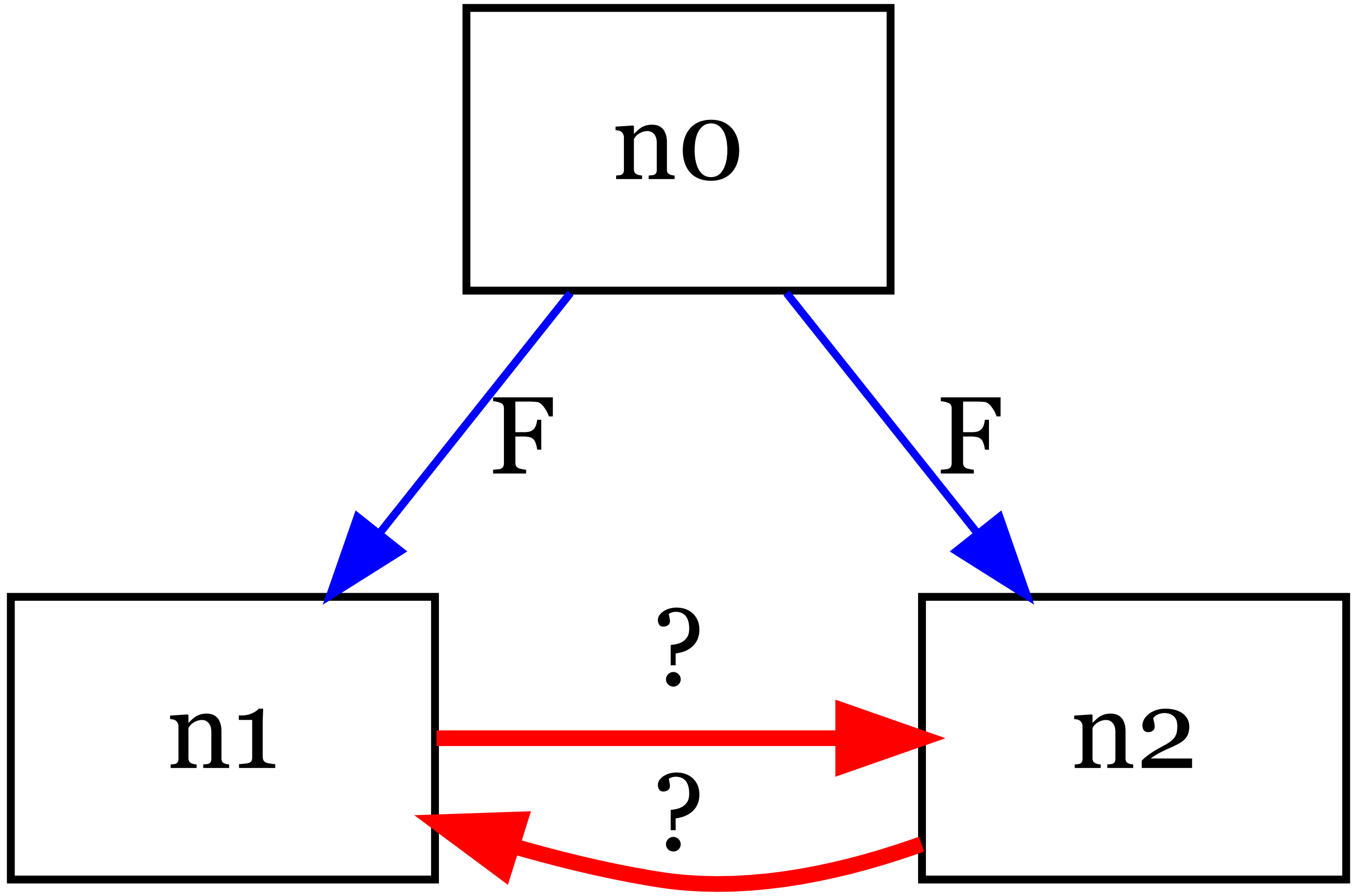
Reducible CFGs - Example

B = Backward Edge; F = Forward Edge



Irreducible CFGs - Example

B = Backward Edge; F = Forward Edge



CFGs based on *Basic Blocks*

In real-word CFGs the nodes are typically based on using basic blocks.

- A basic block is a maximal-length sequence of statements without jumps in and out (and no exceptions are thrown by intermediate instructions).
- A basic blocks based CFG (still) represents the control flow of a single method.

CFGs based on *Basic Blocks* - Example

```
public static int abs(int i) {
    if(i == Integer.MIN_VALUE)
        throw new ArithmeticException();
    if(i < 0)
        i = -i;
    return i;
}
```