Layered Coding Rule Definition and Enforcing Using LLVM

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Motivation: C++ "strange" behaviour

```
class A {
public:
  A();
  virtual void func();
};

class B : public A {
public:
  B() : A() {}
  virtual void func();
};
```

```
A::A() {
  func();
}

B *d = new B();

// A::func or B::func?
```

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Coding rule HICPP 3.3.13

“Do not invoke virtual methods of the declared class
in a constructor or destructor.”

Coding rules

Definition (Coding rules)

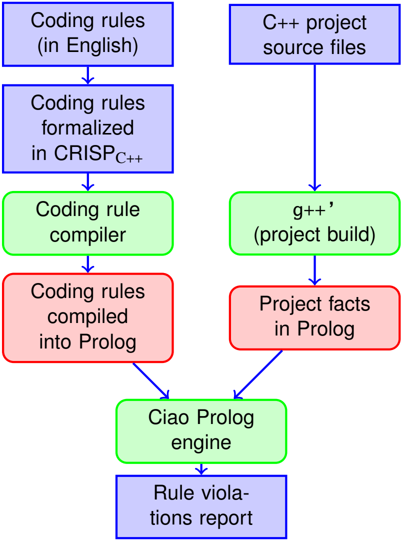
Coding Rules constrain admissible constructs of a language to help produce better code.

- Aim at improving
    - Reliability
    - Security
    - Maintainability
    - Portability
    - …
- Coding standards
    - MISRA-C, MISRA-C++
    - Parasoft's High-Integrity C++ (HICPP)
    - CERT's (CMU) Secure Coding Standards for C, C++, Java
- Need of automation and extensibility
- Problem: big gap between semi-formal definition of rules and actual implementation

Diversity of Coding Rules

- "Do not use the ‘inline’ keyword for member functions."
- "Do not call the malloc() function."
- "Expressions that are effectively Boolean should not be used as operands to operators other than (&&, || and !)."
- "If a virtual function in a base class is not overridden in any derived class, then make it non virtual."
- "All automatic variables shall have been assigned a value before being used."
- "Behaviour should be implemented by only one member function in a class."

Previous prototype based on GCC



Coding rules (in English)

Coding rules formalized in $\text{CRISP}_{\text{C++}}$

Coding rule compiler

Coding rules compiled into Prolog

C++ project source files

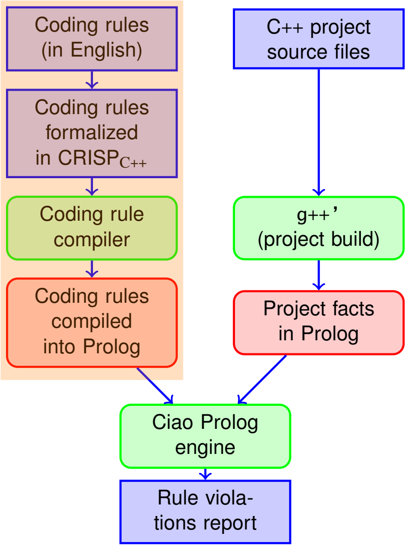
g++' (project build)

Project facts in Prolog

Ciao Prolog engine

Rule violations report

Previous prototype based on GCC



1. Coding rule(s) written **once** in a logic-based formalism called CRISP
2. Extract program information using GCC, and store it
3. Search (using a Prolog engine) for a counterexample

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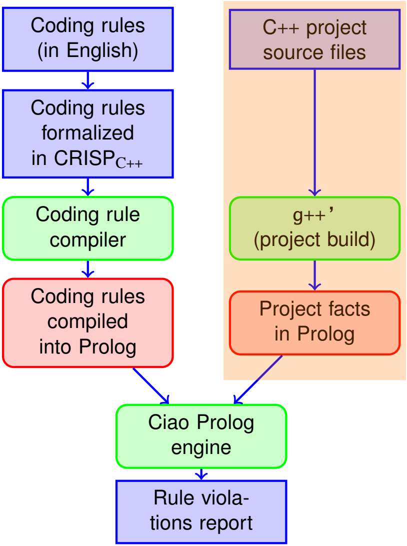

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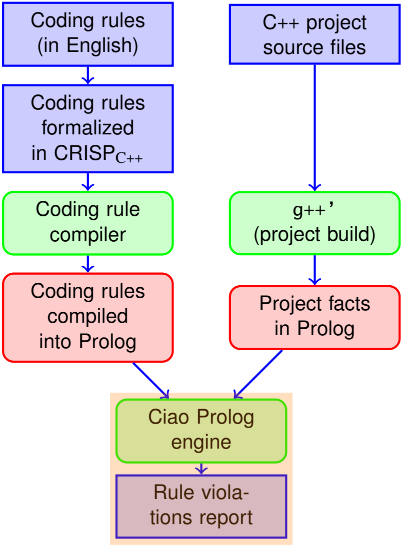

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Example of rule formalisation in CRISP

Rule HICPP 3.3.13

“Do not invoke virtual methods of the declared class in a constructor or destructor.”

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Rule HICPP 3.3.13

"Do not invoke virtual methods of the declared class in a constructor or destructor."

```
rule         HICPP 3.3.13
violated by  Caller : MemberFunction; Callee : VirtualFunction
when         exists R : Record such that (
                     R hasMember Caller
                 and R hasMember Callee
                 and (
                        Caller is Constructor
                     or Caller is Destructor
                 )
                 and Caller calls+ Callee
             )
.
```

CRISP$_{\text{C++}}$ building blocks

- Sorts

  Variable, DataMember, LocalVariable
  Function, MemberFunction, Constructor
  Type, PointerType, Record
  Scope, Namespace, Record, CompoundStatement
  RecordMember

- Predicates

Function	*calls*	Function
Record	*hasImmediateBase*	Record
Variable	*hasType*	NonFunctionType
Function	*hasType*	FunctionType
Function	*isDefinedIn*	Scope
Record	*hasMember*	RecordMember
PointerType	*hasPointedType*	Type
FunctionType	*hasReturnType*	Type

Rules that need some kind of static analysis

Rule HICPP 3.4.2

“Do not return non-const handles to class data from *const* member functions.”

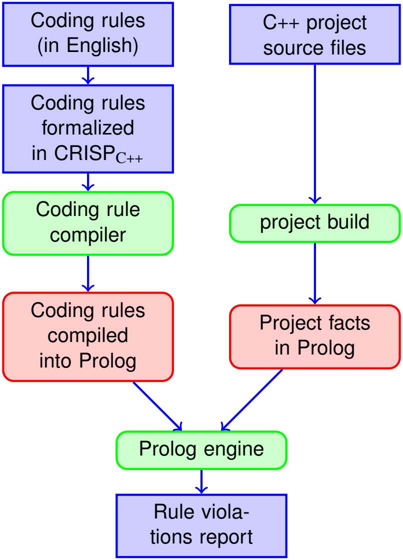
```
class A {
public:
   int* foo() const {
      return m_pa;    // permits subsequent mod. of private data
   }

private:
   int* m_pa;
};

void bar() {
   const A a;
   int* pa = a.foo();
   *pa = 10;          // modifies private data in a!
};
```

Layered rule definition

Integration of information from external analysers



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Layered rule definition

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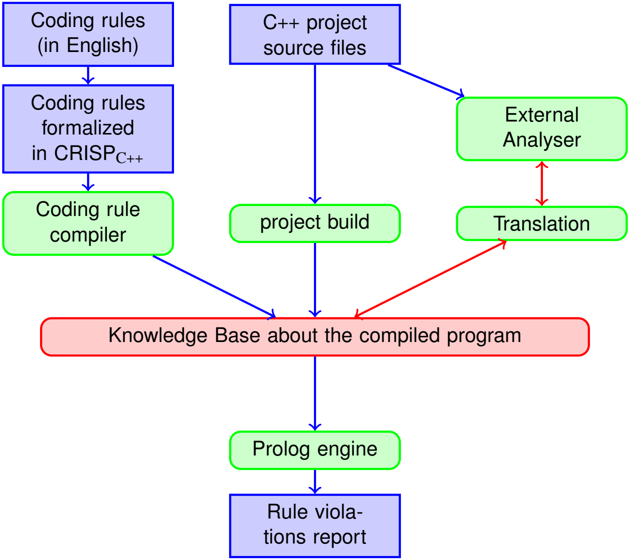

Layered rule definition

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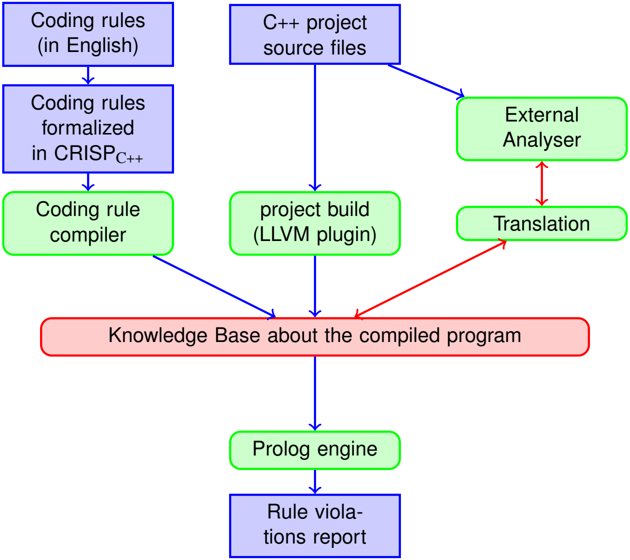

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Coding rule compiler

C++ project source files

project build (LLVM plugin)

External Analyser

Translation

Knowledge Base about the compiled program

Prolog engine

Rule violations report

LLVM: Low-Level Virtual Machine

- "Modular and reusable compiler and toolchain technologies" (http://llvm.org)
- Useful components and features
  - clang C/C++ compiler front-end
  - Well specified code representation (LLVM IR)
  - Target-independent optimiser/analyser (`-analyze`)
  - Alias analysis
  - Link-time optimisation (and analysis)
- LLVM IR is front-end independent
  - Advantage: analysis info can be reused across languages
  - Disadvantage: need to keep track of the correspondence between source-level constructions and IR elements

Alias analysis in LLVM

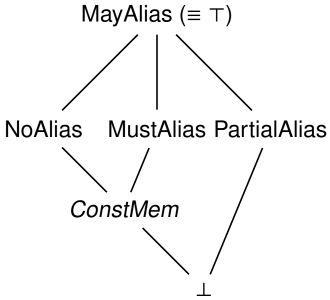
- API

```
enum AliasResult { NoAlias      = 0 , MayAlias  = 1
                 , PartialAlias = 2 , MustAlias = 3 }

virtual AliasResult
alias (const Location &LocA, const Location &LocB);
```

- A `Location` represents a memory location in the LLVM IR (assembler) code: Pointer + Size
- Diversity of implementations
  - `-basicaa`
  - `-steens-aa`: Steensgaard's algorithm
  - `-ds-aa`: Data Structure Analysis algorithm
  - `-scev-aa`: Scalar Evolution queries
  - `-tbaa`: Type-based

A domain for alias analysis results



- Complementary LLVM API

```
virtual bool pointsToConstantMemory (const Location &Loc);
```

- CRISP expressions for alias queries, examples:

  L1 *alias* L2 $\sqsubseteq$ NoAlias

  L1 *alias* L2 = PartialAlias

- Idea: use the above expressions as constraints in CLP

LLVM IR for counterexample of Rule HICPP 3.4.2

```
class A {
public:
  int* foo(bool b) const {
    int* local = 0;
    if (b) local = m_pa;
    return local;
  }
private:
  int* m_pa;
};
```

```
  define linkonce_odr i32* @_ZNK1A3fooEb(%class.A* nocapture %this, i1 zeroext %b)
    nounwind readonly align 2 {
  entry:
    tail call void @llvm.dbg.value(metadata !{%class.A* %this}, i64 0, metadata !28)
    tail call void @llvm.dbg.value(metadata !42, i64 0, metadata !30)
    br i1 %b, label %if.then, label %if.end

  if.then:                                          ; preds = %entry
    %m_pa = getelementptr inbounds %class.A* %this, i64 0, i32 0
    %tmp2 = load i32** %m_pa, align 8
    tail call void @llvm.dbg.value(metadata !{i32* %tmp2}, i64 0, metadata !30)
    br label %if.end

  if.end:                                           ; preds = %if.then, %entry
    %local.0 = phi i32* [ %tmp2, %if.then ], [ null, %entry ]
    ret i32* %local.0
  }
```

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    int* local = 0;
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    return local;
  }
private:
  int* m_pa;
};
```

- New CRISP predicates

MemberFunction	*hasThisLocation*	Location
Function	*returnsLocation*	Location
Location	*isGottenAsOffsetFrom*	Location

```
  define linkonce_odr i32* @_ZNK1A3fooEb(%class.A* nocapture %this, i1 zeroext %b)
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    tail call void @llvm.dbg.value(metadata !{%class.A* %this}, i64 0, metadata !28)
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    br i1 %b, label %if.then, label %if.end

  if.then:                                          ; preds = %entry
    %m_pa = getelementptr inbounds %class.A* %this, i64 0, i32 0
    %tmp2 = load i32** %m_pa, align 8
    tail call void @llvm.dbg.value(metadata !{i32* %tmp2}, i64 0, metadata !30)
    br label %if.end

  if.end:                                           ; preds = %if.then, %entry
    %local.0 = phi i32* [ %tmp2, %if.then ], [ null, %entry ]
    ret i32* %local.0
  }
```

CRISP definition of Rule HICPP 3.4.2

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Rule HICPP 3.4.2

“Do not return non-const handles to class data from const member functions.”

```
rule          HICPP 3.4.2
violated by   M : ConstMemberFunction
when          exists Data, This, Ret : Location;
                     FuncT, RetT, PointT : Type
              such that (
                      M hasType T
                  and T hasReturnType RetT
                  and RetT is PointerType
                  and RetT hasPointedType PointT
                  and not PointT is ConstType
                  and M hasThisLocation This
                  and M returnsLocation Ret
                  and Data isGottenAsOffsetFrom This
                  and Ret alias Data ⋢ NoAlias
              )
.
```

Future work

- Define more rules that need Alias Analysis and find the right abstractions of low-level concepts.
- Find other analyses useful for formalising coding rules and define suitable domains for them.
- Devise a method for solving analysis domain constraints.
- Study rules in which results from different analyses are necessary, and how to combine them.