Performing Source-to-Source Transformations with Clang

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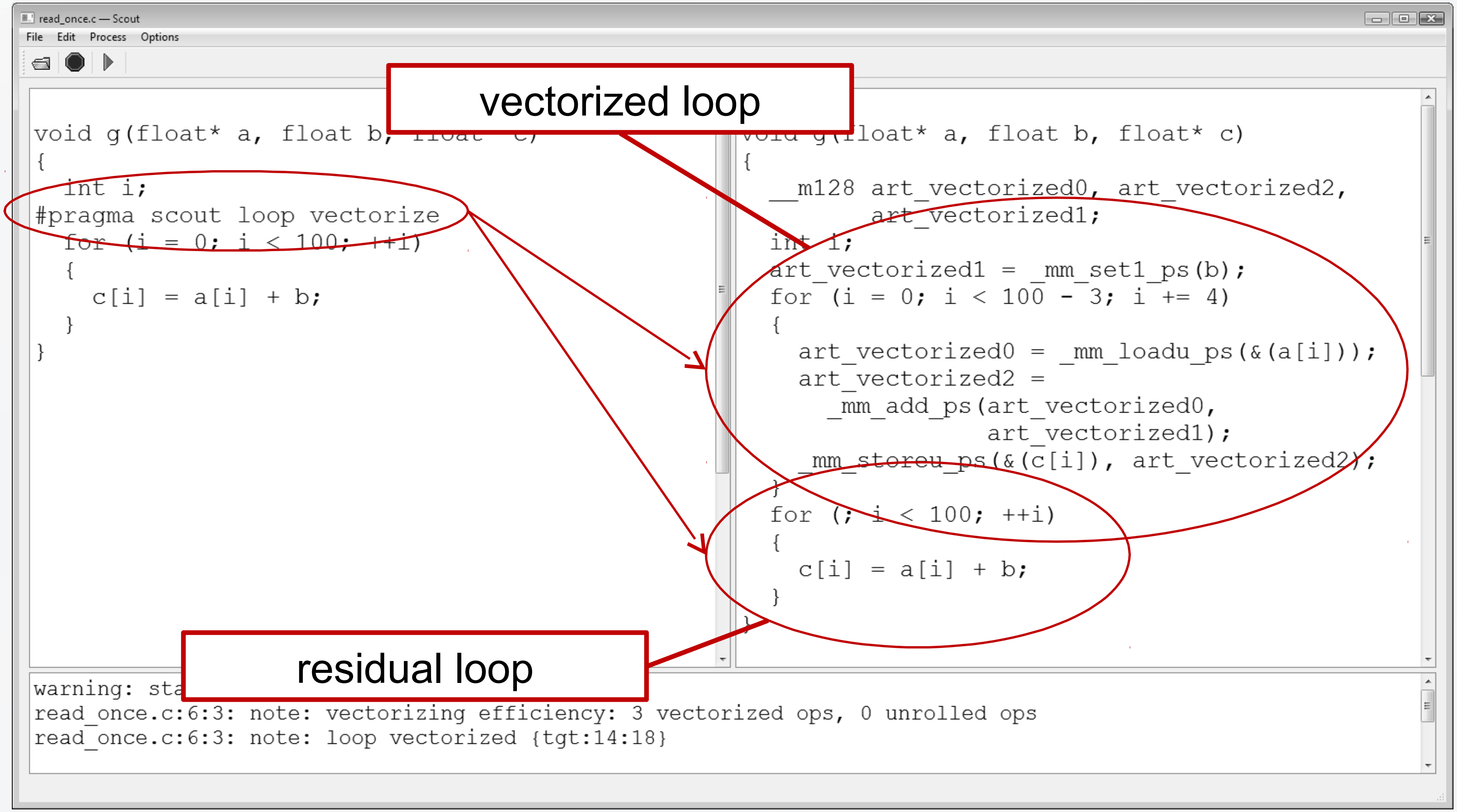
Agenda today

1. Some disclaimers (sort of)
   - and some background: source-to-source vectorization
2. Our current solution (working with clang 3.2)
   - traversing the AST
   - editing the AST
3. Best (or worth discussing) practices
   - merging ASTs
   - using TreeTransform
   - cloning
4. Future Directions

Disclaimers

- no strategical elaboration of the source-to-source approach
  - instead a lot of code
- we transfom clang's AST!
  - actually not allowed
  - source-to-source transformation □ source-to-source compilation
- all blue highlighted code works
  - open source and downloadable at `http://scout.zih.tu-dresden.de/`
  - project started in 2009 □ meanwhile better approaches for some tasks

The big picture: Scout



vectorized loop

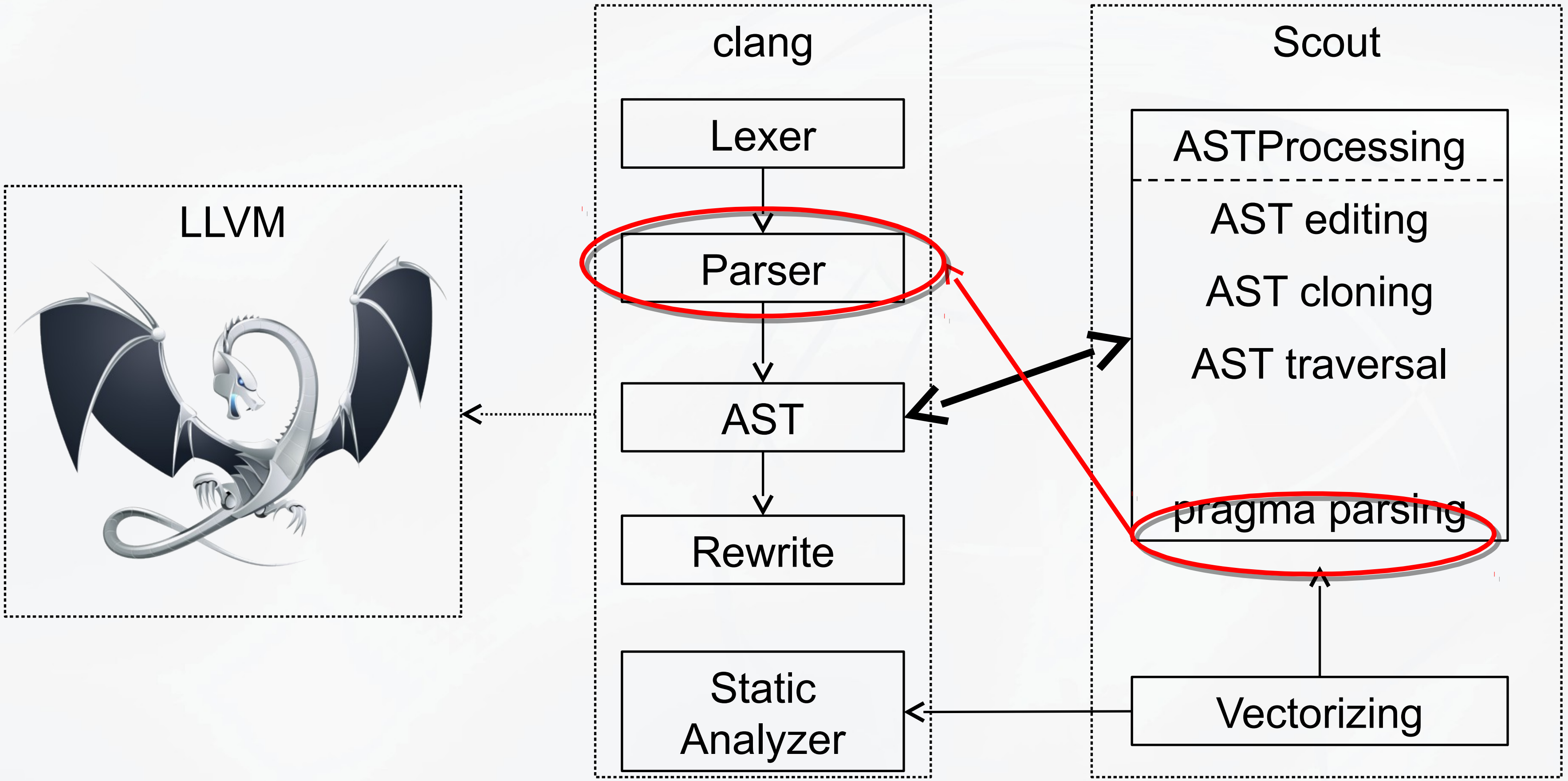
```
void g(float* a, float b, float* c)
{
  int i;
#pragma scout loop vectorize
  for (i = 0; i < 100; ++i)
  {
    c[i] = a[i] + b;
  }
}
```

```
void g(float* a, float b, float* c)
{
  __m128 art_vectorized0, art_vectorized2,
         art_vectorized1;
  int i;
  art_vectorized1 = _mm_set1_ps(b);
  for (i = 0; i < 100 - 3; i += 4)
  {
    art_vectorized0 = _mm_loadu_ps(&(a[i]));
    art_vectorized2 =
      _mm_add_ps(art_vectorized0,
                 art_vectorized1);
    _mm_storeu_ps(&(c[i]), art_vectorized2);
  }
  for (; i < 100; ++i)
  {
    c[i] = a[i] + b;
  }
}
```

residual loop

```
warning: sta
read_once.c:6:3: note: vectorizing efficiency: 3 vectorized ops, 0 unrolled ops
read_once.c:6:3: note: loop vectorized {tgt:14:18}
```

The medium picture: Components



LLVM

clang

Lexer

Parser

AST

Rewrite

Static Analyzer

Scout

ASTProcessing

AST editing

AST cloning

AST traversal

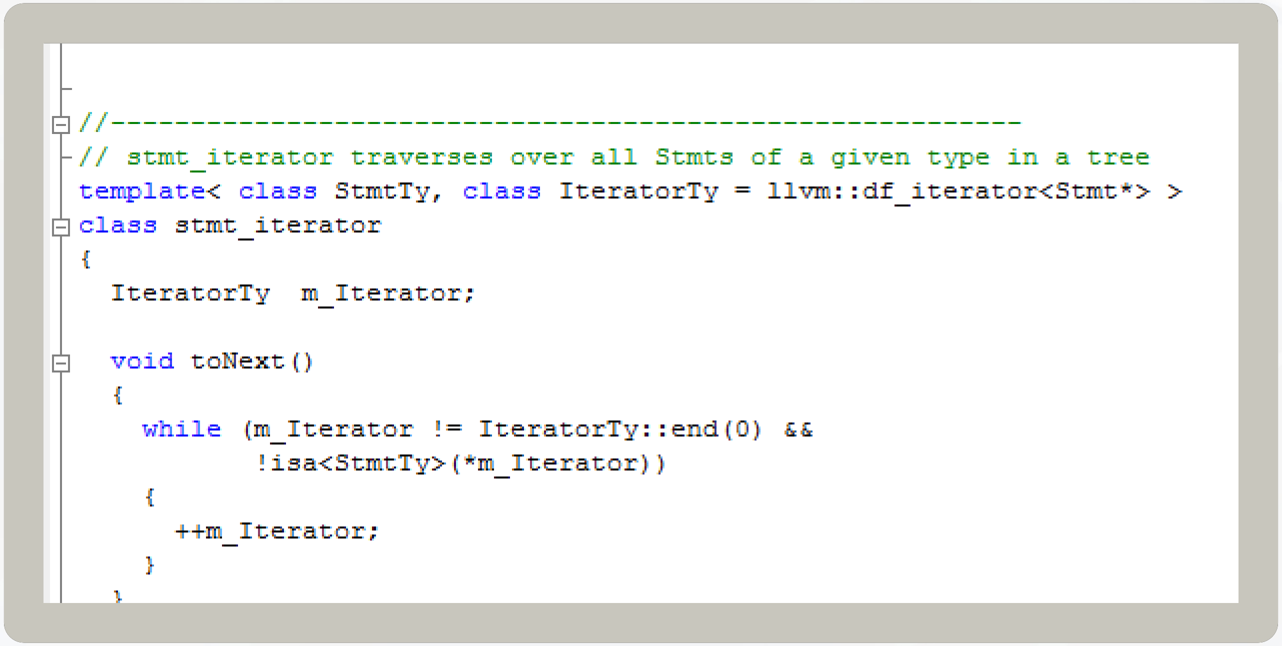
pragma parsing

Vectorizing

The Detailed Picture: Code

2. Our current solution (working with clang 3.2)

AST creation and AST editing



```
//----------------------------------------------------------
// stmt_iterator traverses over all Stmts of a given type in a tree
template< class StmtTy, class IteratorTy = llvm::df_iterator<Stmt*> >
class stmt_iterator
{
  IteratorTy  m_Iterator;

  void toNext()
  {
    while (m_Iterator != IteratorTy::end(0) &&
           !isa<StmtTy>(*m_Iterator))
    {
      ++m_Iterator;
    }
  }
```

AST Creation

- central class `StmtEditor`
  - interface for the creation of variables, expressions and statements

```
class StmtEditor {
public:
  ASTContext& Ctx();

  BinaryOperator* Assign_(Expr* lhs, Expr* rhs);
  BinaryOperator* Add_(Expr* lhs, Expr* rhs);
  DeclRefExpr* DeclRef_(ValueDecl* VD);

  Expr* Int_(int value);                 // simple 32 bit integer
  Expr* Float_(const llvm::APFloat& value, QualType t);

  VarDecl* VarDecl_(QualType tmpType, Expr* init = 0,
    const tOriginalNameInfo& originalVar = tOriginalNameInfo());

  // aso.
};
```

`clangAddons/include/clang/ASTProcessing/StmtEditor.h`

AST Creation

- best way: access the member functions of `StmtEditor` by derivation:

```
class LoopBlocker : StmtEditor {
  void block(ForStmt* Node) {
    DeclStmt *temp = TmpVar_(Ctx().IntTy), *temp_bound = TmpVar_(Ctx().IntTy),
             *i_bound = TmpVar_(Ctx().IntTy);
    Stmt* innerBody[3] = {
      // temp_bound = i_bound - loopVar;
      Assign_(DeclRef_(temp_bound), Sub_(DeclRef_(i_bound), DeclRef_(loopVar))),
      // temp_bound = temp_bound < tileSize ? temp_bound : tileSize;
      Assign_(DeclRef_(temp_bound), Conditional_(LT_(DeclRef_(temp_bound),
        Int_(tileSize)), DeclRef_(temp_bound), Int_(tileSize))),
      // for (temp=0; temp < temp_bound; ++temp) ...
      For_(Assign_(DeclRef_(temp),Int_(0)), LT_(DeclRef_(temp),DeclRef_(temp_bound)),
        PreInc_(DeclRef_(temp)), Node->getBody())
     };
     Node->setBody(Compound_(innerBody));
  }
};
```

clangAddons/include/clang/ASTProcessing/LoopBlocking.cpp

AST Creation

- transformation performed:

```
for (...; i < z; ++i)
  for-body
```

```
for (...; i < z; ++i) {

  temp_bound = i_bound - i;
  temp_bound = temp_bound < tileSize ? temp_bound : tileSize;
  for ( temp = 0; temp < temp_bound; ++temp)
    for-Body;

}
```

- things missing:
  - implementation of `StmtEditor`
  - replace loop index `i` with `temp` mutating an AST enters the true minefield

AST Creation

- creating AST nodes:
  - no problem at statement level

```
class StmtEditor {
  static const SourceLocation nopos; // helper
  IfStmt* If_(Expr* cond, Stmt* then, Stmt* else) {
    return new (Ctx()) IfStmt(Ctx(), nopos, 0, cond, then, nopos, else));
  }
};
```

AST Creation

- creating AST nodes:
  - implementation of the most possible naive approach at expression level:

```
BinaryOperator* BinOp_(Expr* lhs, Expr* rhs, BinaryOperator::Opcode opc) {
  if (opc >= BO_MulAssign && opc <= BO_OrAssign)
  {
    return new(Ctx())CompoundAssignOperator(lhs, rhs, opc, lhs->getType(),
      VK_RValue, OK_Ordinary, lhs->getType(), lhs->getType(),
      nopos, false));
  }
  QualType resultType = (BinaryOperator::isComparisonOp(opc) ||
    BinaryOperator::isLogicalOp(opc)) ? Ctx().BoolTy : lhs->getType();
  return new(Ctx())BinaryOperator(lhs, rhs, opc, resultType,
    VK_RValue, OK_Ordinary, nopos, false));
}
```

- fails for various reasons don't try this at home
  - requires redirection to `Sema`

AST Editing

- editing AST nodes
  - replacing statements in compound statements is no problem
  - general purpose replacement
    - requires parent map internally maintained by `StmtEditor`
    - and once again: works smoothly at statement level only, but replacing sub-expressions is dangerous

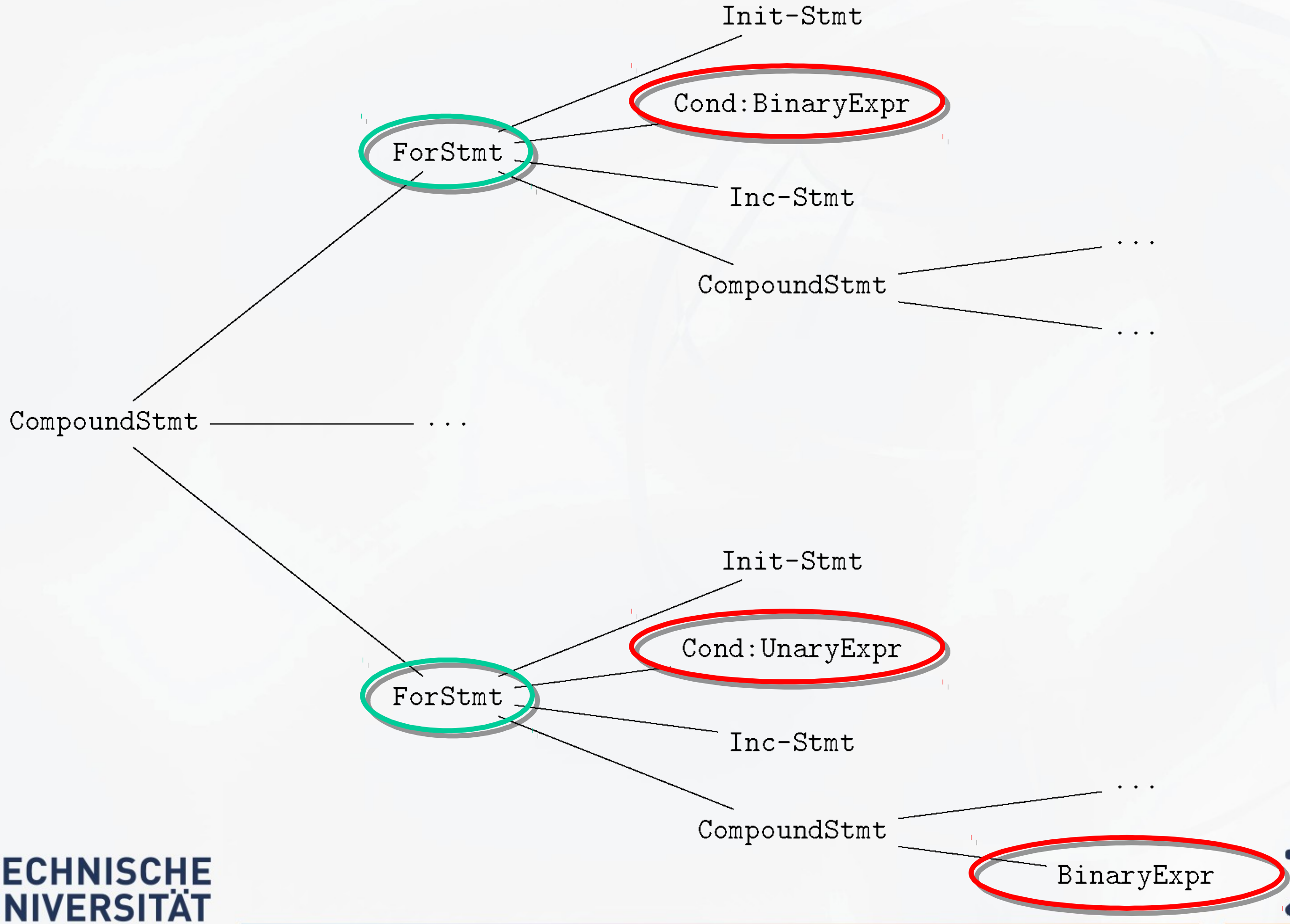
```
class StmtEditor {
  // all staments of S are replaced by Stmts
  void replaceStmts(CompoundStmt* S, Stmt **Stmts, unsigned NumStmts);


  // replaces from in the parent with newStmt, returns newStmt
  Stmt* replaceStatement(Stmt* from, Stmt* newStmt);
};
```

However: all this code shown here is in production
 clang can do this kind of transformations!

AST Traversing

- `template<typename Derived> class RecursiveASTVisitor;`
  - processing of different AST classes in one traversal
  - uses CRTP requires sub-classing



AST Traversing

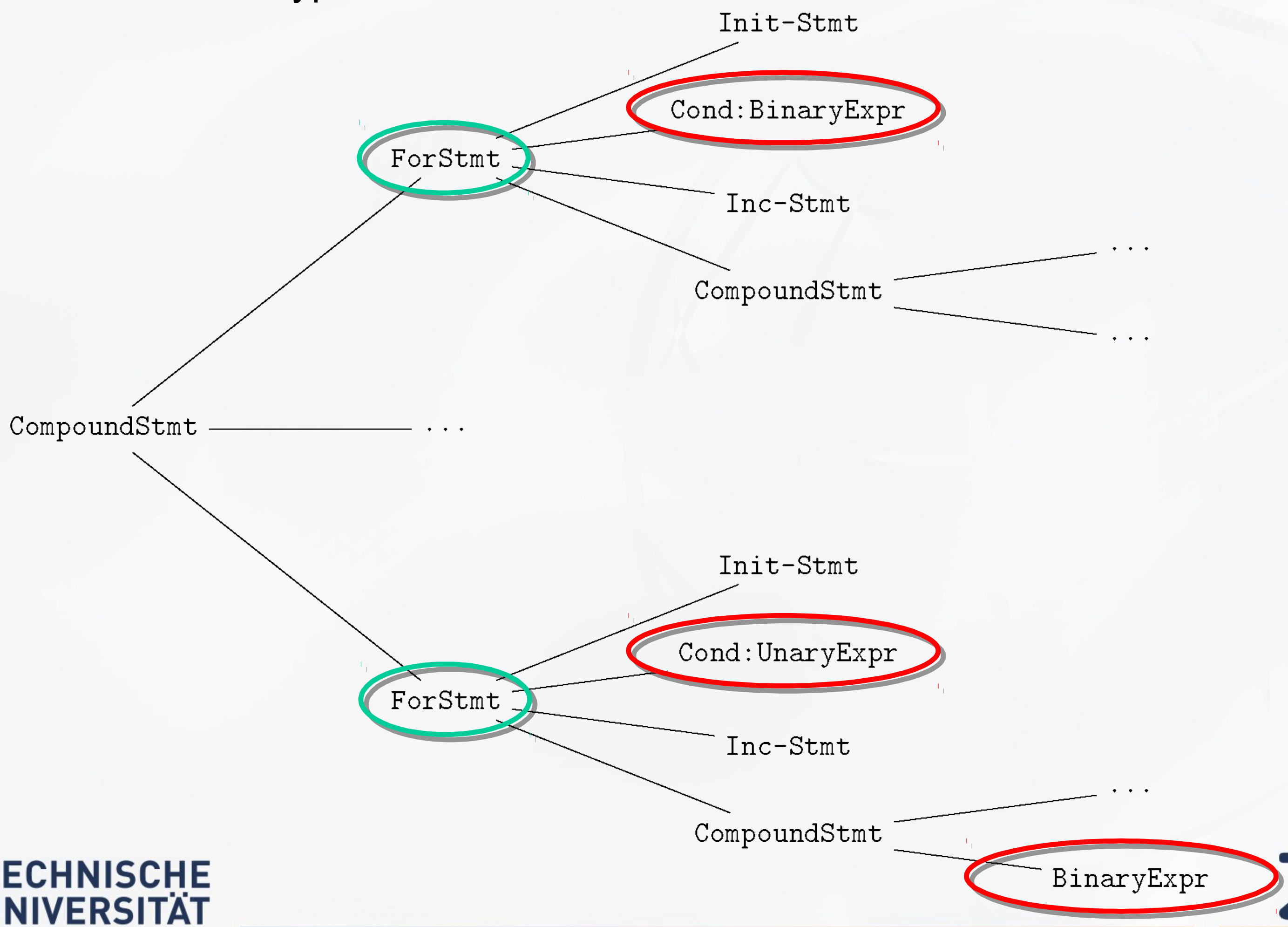
- `template<class StmtTy> class stmt_iterator`
  - forward iterator for a particular AST class given by `StmtTy`
  - implementation based on `llvm::df_iterator<Stmt*>`
  - usable in floating code:

```
//...
for (stmt_iterator<ForStmt> i = stmt_ibegin(root),
     e = stmt_iend(root); i != e; ++i)
{
  ForStmt* node = *i;
  //...
}
//...
```

clangAddons/include/clang/ASTProcessing/StmtTraversal.h

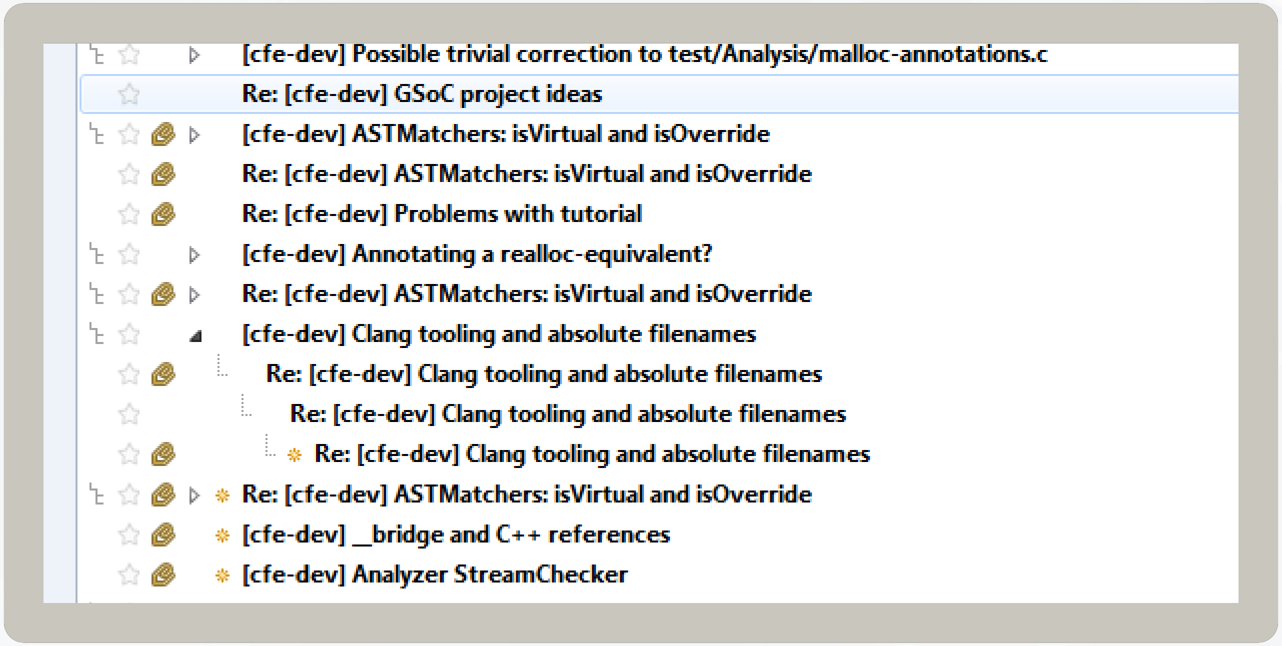
AST Traversing

- `template<class StmtTy> class stmt_iterator`
  - processes only one AST class per traversal
  - doesn't handle type decls



3. Best (or worth discussing) practices

questions raised on cfe-dev and our solutions



[cfe-dev] Possible trivial correction to test/Analysis/malloc-annotations.c
Re: [cfe-dev] GSoC project ideas
[cfe-dev] ASTMatchers: isVirtual and isOverride
Re: [cfe-dev] ASTMatchers: isVirtual and isOverride
Re: [cfe-dev] Problems with tutorial
[cfe-dev] Annotating a realloc-equivalent?
Re: [cfe-dev] ASTMatchers: isVirtual and isOverride
[cfe-dev] Clang tooling and absolute filenames
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Re: [cfe-dev] ASTMatchers: isVirtual and isOverride
[cfe-dev] __bridge and C++ references
[cfe-dev] Analyzer StreamChecker

Cloning

- cloning parts of an AST is important for many transformation tasks
  - e.g. function inlining, loop unrolling aso.
  - just search for "clone" on cfe-dev

```
class StmtClone : public StmtVisitor<StmtClone, Stmt*>
{
public:

  template<class StmtTy>
  StmtTy* Clone(StmtTy* S) {
    return static_cast<StmtTy*>(Visit(S));
  }

  Stmt* StmtClone::VisitStmt(Stmt*) {
    assert(0 && "clone incomplete");
    return NULL;
  }

  // visitor functions
};
```

clangAddons/include/clang/ASTProcessing/StmtClone.h

Cloning

- cloning parts of an AST is important for many transformation tasks
  - implementation clones recursively
  - as volatile as the AST classes

```
class StmtClone : public StmtVisitor<StmtClone, Stmt*>
{
public:
  Stmt* VisitBinaryOperator (BinaryOperator *Node)
  {
    BinaryOperator* result = new (Ctx) BinaryOperator(
      Clone(Node->getLHS()), Clone(Node->getRHS()),
      Node->getOpcode(), Node->getType(), Node->getValueKind(),
      Node->getObjectKind(), Node->getOperatorLoc(),
      Node->isFPContractable());

    result->setValueDependent(Node->isValueDependent());
    result->setTypeDependent(Node->isTypeDependent());
    return result;
  }

};
```

clangAddons/lib/ASTProcessing/StmtClone.cpp

Cloning

- cloning parts of an AST is important for many transformation tasks
  - is `TreeTransform` the better cloner?

```
struct StmtClone : TreeTransform<StmtClone>                    untested
{
  // ???
  bool AlwaysRebuild() { return true; } // this essentially clones
  // the cast might fail (e.g. for ImplicitCastExpr):
  template<class StmtTy>
  StmtTy* Clone(StmtTy* S) {
    return static_cast<StmtTy*>(Transform(S).get());
  }
};
```

Using TreeTransform

- task: transform `a += b` to `a = a + b`
  - ▯ use `TreeTransform`

```
//...
#include "clang/AST/StmtVisitor.h"
#include "../lib/Sema/TreeTransform.h"

struct CompoundAssignTransform : TreeTransform<CompoundAssignTransform>
{
  CompoundAssignTransform (Sema& s) :
    TreeTransform<CompoundAssignTransform>(s) {}

  //...
};
```

clangAddons/lib/Vectorizing/Analysis.cpp

Using TreeTransform

- task: transform `a += b` to `a = a + b`
  - creating `TreeTransform`

```
class RewriteInline : public SemaConsumer
{
  CompilerInstance& CI;
public:
  RewriteInline(CompilerInstance &CInst) : CI(CInst) {}


  virtual void InitializeSema(Sema &S) { CI.setSema(&S); }
  virtual void ForgetSema() { CI.takeSema(); }


  virtual void HandleTranslationUnit(ASTContext &C);
};
```

clangAddons/lib/Interface/Interface.cpp

Using TreeTransform

- task: transform `a += b` to `a = a + b`
  - perform the transformation

```
struct CompoundAssignTransform : TreeTransform<CompoundAssignTransform>
{
  //...
  bool AlwaysRebuild() { return true; } // this essentially clones
  ExprResult TransformCompoundAssignOperator(CompoundAssignOperator *E)
  {
    BinaryOperator::Opcode binOpc = transformOpc(E->getOpc());
    ExprResult lhsClone = TransformExpr(E->getLHS());
    ExprResult rhs = RebuildBinaryOperator(E->getOperatorLoc(),
                       binOpc, lhsClone.get(), E->getRHS());
    return RebuildBinaryOperator(E->getOperatorLoc(),
             BO_Assign, E->getLHS(), rhs.get());
};
```

clangAddons/lib/Vectorizing/Analysis.cpp

Using TreeTransform

- task: transform `a += b` to `a = a + b`
  - creating and using the transformation

```
int VisitCompoundAssignOperator(CompoundAssignOperator* Node)
{
  Sema::ContextRAII raiiHolder(getSema(), &getFnDecl());
  ExprResult res = CompoundAssignTransform(getSema()).
    TransformCompoundAssignOperator(Node);
  if (res.isInvalid()
  {
    return ERROR;
  }
  replaceStatement(Node, res.get());
  return SUCCESS;
}
```

clangAddons/lib/Vectorizing/Analysis.cpp

AST Merging

- first way: textual level
  - preprocess complete files
  - requires the same language settings
  - used to get function bodies for inlining

```
std::stringstream completeSource;
const std::list<std::string>& preprocessedFiles = //...

for (std::list<std::string>::const_iterator i =
     preprocessedFiles.begin(), e = preprocessedFiles.end();
     i != e; ++i) {

  if (*i != pFileName)    // [#717]: don't self-preprocess
    completeSource << "#include \"" << *i << "\"\n";

}

completeSource << "#line 1\n";
completeSource << actualSource;
```

clangAddons/lib/Interface/Application.cpp:processFile

AST Merging

- second way: `ASTImporter`
  - import code snippets
  - the Scout-specific class `Configuration` holds a source AST

```
ASTImporter* create(CompilerInstance& compiler, // target AST
                    Configuration& config)      // holds source AST
{
  return new ASTImporter(
    compiler.getASTContext(), compiler.getFileManager(),
    config.getASTContext(), config.getFileManager(),
    /*minimalImport=*/true);
}
```

clangAddons/lib/Vectorizing/IntrinsicCollector.cpp

AST Merging

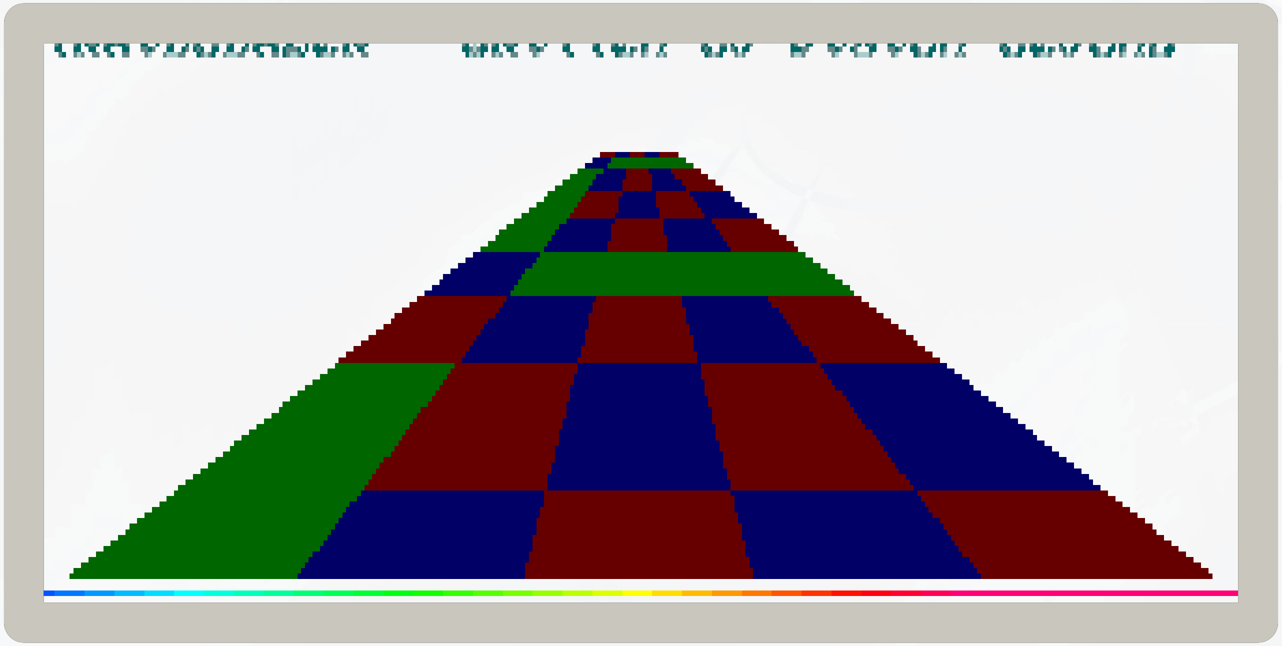
- second way: `ASTImporter`
  - getting a persistent `ASTContext` and `FileManager` from the source compiler in a separate compilation step:

```
class ParseConfigurationConsumer : public ASTConsumer
{
  Configuration&  config;
  llvm::OwningPtr<CompilerInstance>& compiler;

  virtual void HandleTranslationUnit(ASTContext &C)
  {
    //...
    if (!compiler->getDiagnostics().hasErrorOccurred()) {
      config.m_ASTContext.reset(&compiler->getASTContext());
      config.m_FileManager.reset(&compiler->getFileManager());

      compiler->resetAndLeakASTContext();
      compiler->resetAndLeakFileManager();
    }
  }
};
```

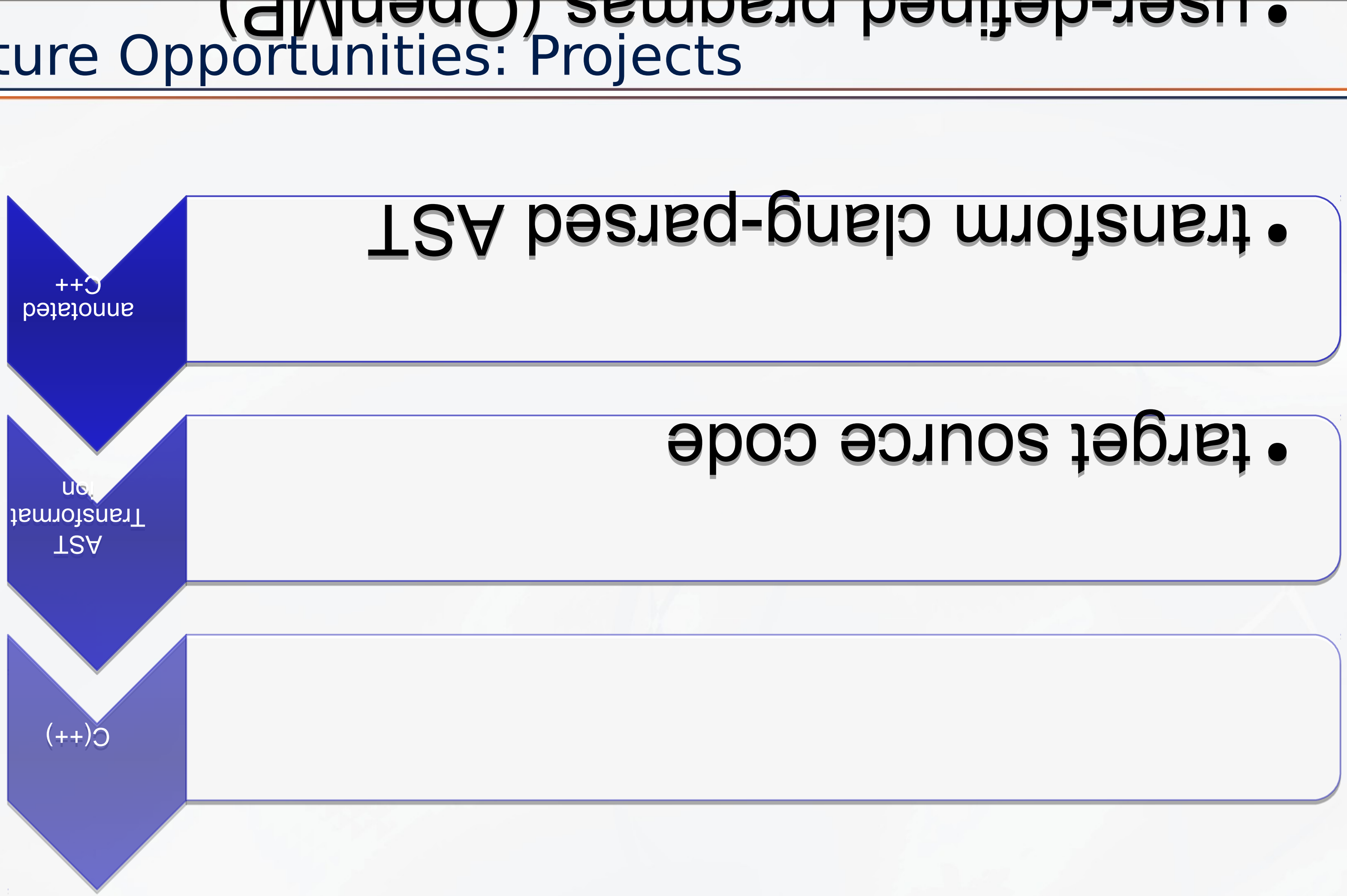
clangAddons/lib/Vectorizing/Configuration.cpp

4. Future Directions

Can Clang become a suitable tool for source-to-source transformations?



Future Opportunities: Projects



- user-defined pragmas (OpenMP)

annotated C++

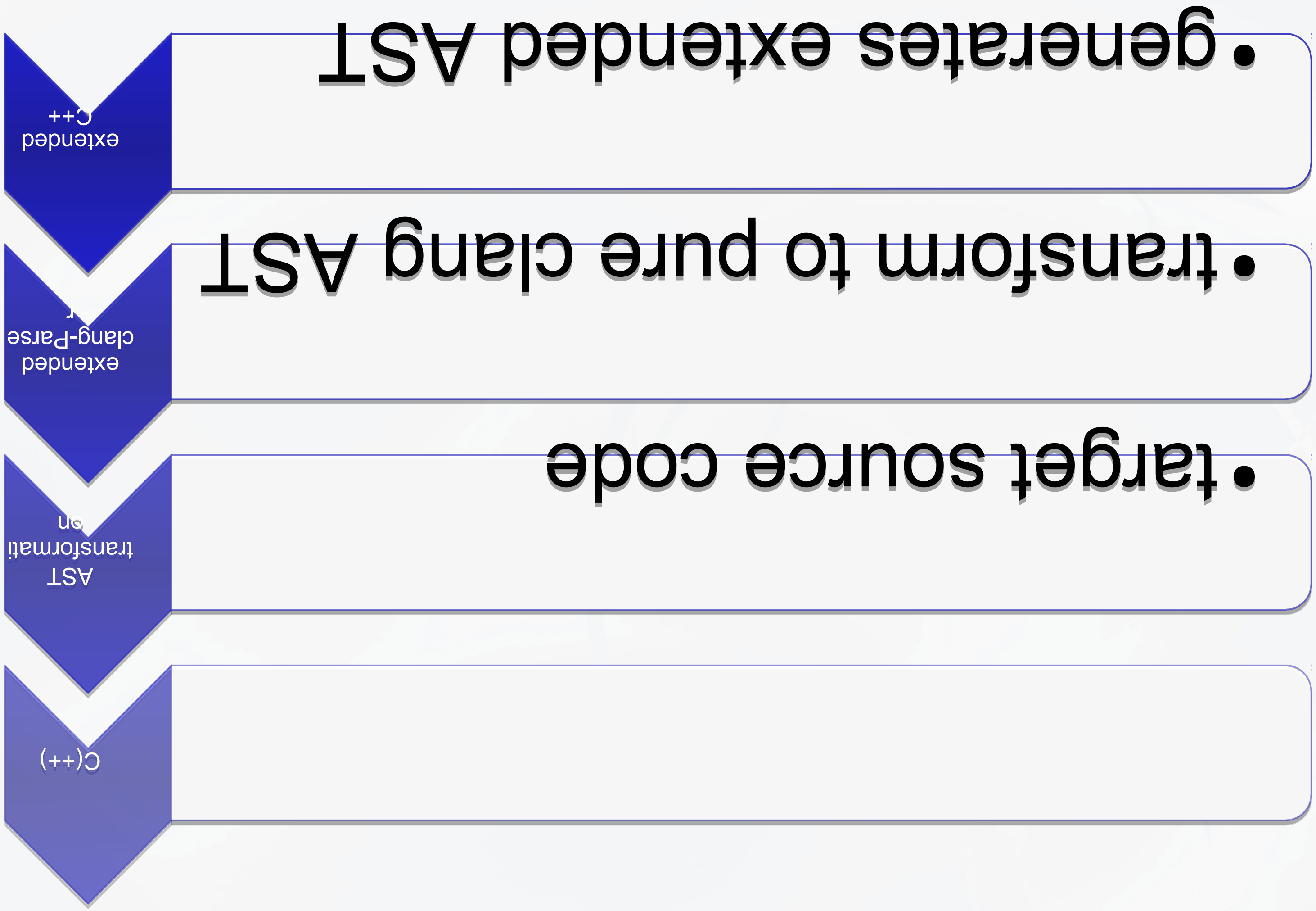
- transform clang-parsed AST

AST Transformation

- target source code

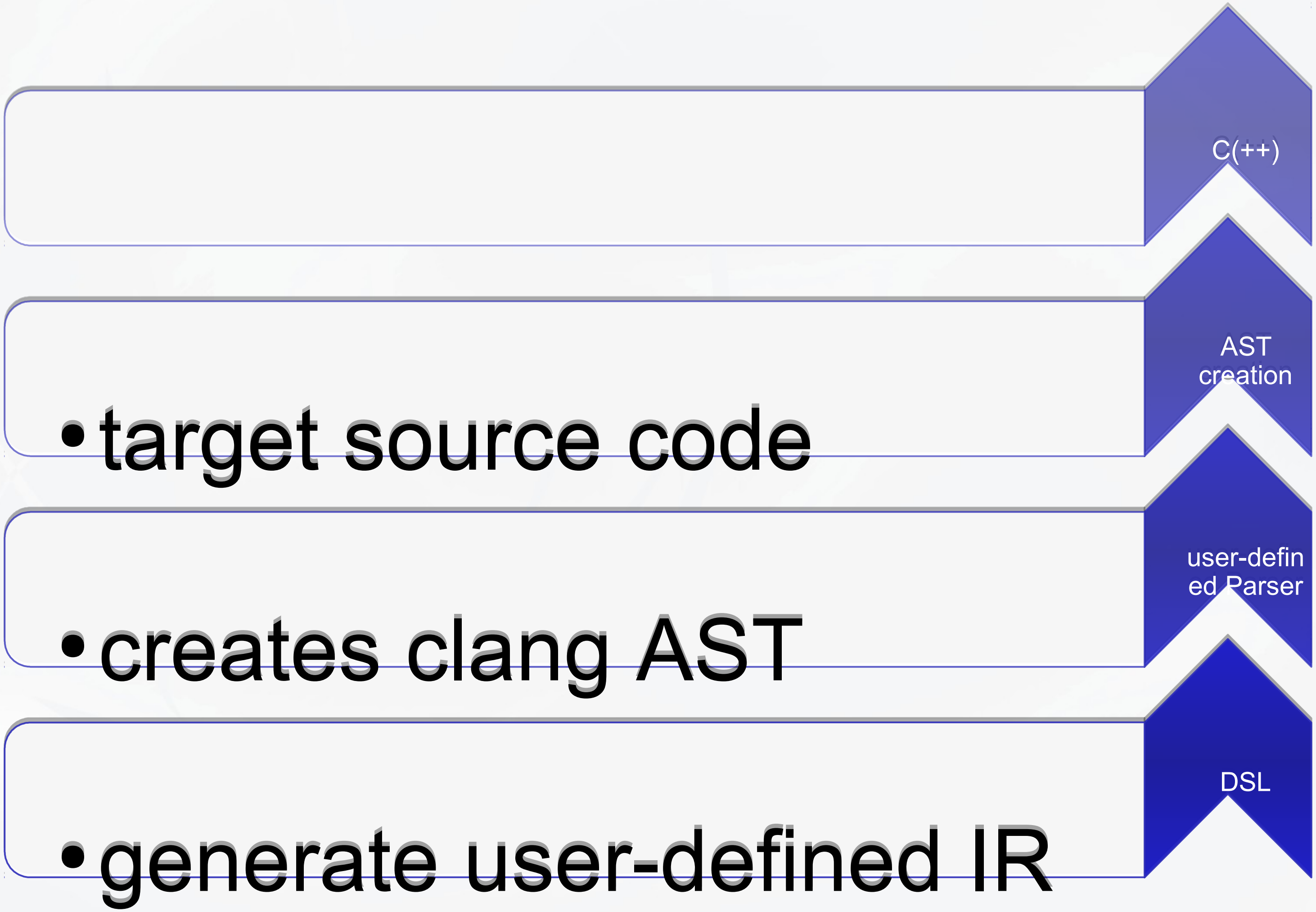
C(++)

Future Opportunities: Projects



- e.g. UPC
- generates extended AST
- transform to pure clang AST
- target source code

Future Opportunities: Projects



- target source code
- creates clang AST
- generate user-defined IR
- user-defined language

Future: Zoom out to Strategy

ZIH
Center for Information Services &
High Performance Computing
Research
Partners?

Discussion

http://scout.zih.tu-dresden.de/

Future Opportunities: Code

- things that very probably might not work:
  - mirror the AST □ duplicates functionality
  - rewrite, parse and rebuild the AST as often as possible □ too slow
- keep the `StmtEditor` interface
  - extended with operator overloading
- backup the implementation with `Sema`
  - enriched with machine-evaluatable diagnostics
  - hard task no.1: maintain the `Sema` state
  - hard task no.2: replacing statements

Can Clang become a suitable tool for source-to-source transformations?

Is the integration of an ASTProcessing lib in clang desired?

Using TreeTransform

- task: transform `a += b` to `a = a + b`
  - old code never really worked
  - example from one year ago:

```
// x += y  x = x + y for arbitrary ops:
typedef CompoundAssignOperator CAO;
for (stmt_iterator<CAO> i = stmt_ibegin<CAO>(Root),
                        e = stmt_iend<CAO>(Root); i != e; ++i) {
  CAO* Node = *i;
  BinaryOperator::Opcode binOpc = transformOpc(Node->getOpc());
  Expr* clonedLhs = Clone_(Node->getLHS());
  clonedLhs->setValueKind(VK_RValue);       // the tricky part
  replaceStatement(
    Node,
    Assign_(Node->getLHS(),
            BinaryOp_(clonedLhs, Node->getRHS(), binOpc)));
}
```