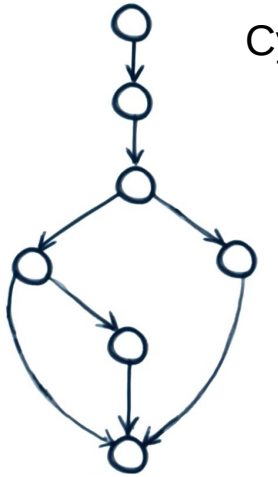
Metric Based
Code Parallelisability Analyzer

THE UNIVERSITY *of* EDINBURGH
informatics

EPSRC Centre for Doctoral Training in
Pervasive Parallelism

Basic Idea

Software quality



Cyclomatic Complexity (CC)

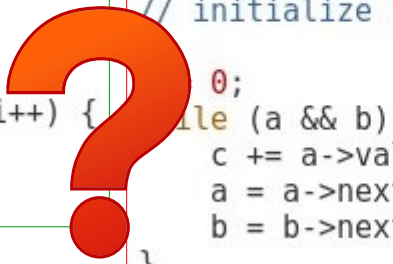
Software parallelisability

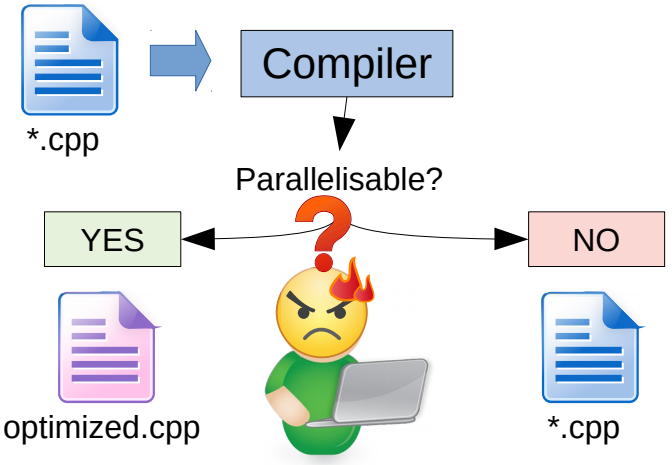
```
int a[1000];
int b[1000];
int c;

// initialize arrays

c = 0;
for (int i = 0; i < 1000; i++) {
    c += a[i] * b[i];
}
```

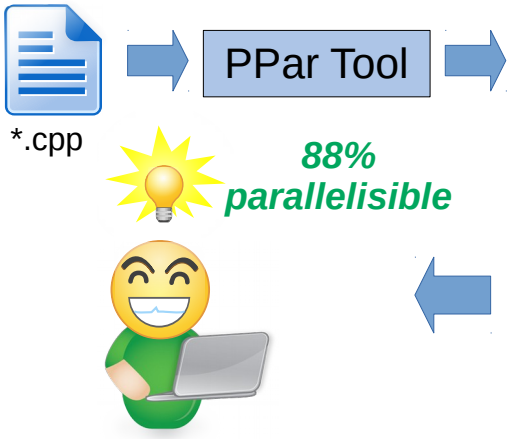
Good Score

```
Node *a;
Node *b;
int c;

// initialize linked lists

    0;
le (a && b) {
    c += a->val * b->val;
    a = a->next;
    b = b->next;
}
```

Bad Score







Loop Proportion Metric Set:

loop-absolute-size: 22
loop-payload-fraction: 0,55
loop-proper-sccs-number: 1

Loop Cohesion Metric Set:

iterator-payload-total-cohesion: 13 %
iterator-payload-non-cf-cohesion: 2,17 %
iterator-payload-mem-cohesion: 0 %
critical-payload-total-cohesion: 29,4 %
critical-payload-non-cf-cohesion: 11,8 %
critical-payload-mem-cohesion: 0 %

Current Project State (~4-5 months)

- Devised an initial set of parallelisability metrics (*17 metrics*)
- Developed a tool for metrics collection (*~4300 lines of C++ code*) (*used iterator recognition work as a reference*)
- Prepared a testing framework (*kindly provided by Christos Vasiladiotis*), allowing to run NAS benchmarks through developed tool
- Tool and initial metrics are debugged and validated with small hand-written test programs

- Tool developed as a dynamic library (.so) to be plugged into LLVM 6.0
- Uses standard LLVM passes to build dependence graph of the source code
- Built graphs might be printed and studied by a human reader
- Tool computes a set of metrics on the built dependence graphs

GitHub https://github.com/av-maramzin/PParMetrics

Things to be done

Minimal plan (has to be done in ~2,5 months)

- Learn NAS benchmarks (11 benchmarks)
- Debug and validate metrics on NAS benchmarks
- Analyze received results
- Write MSc by Research thesis

Desired plan (requires more than ~2,5 months)

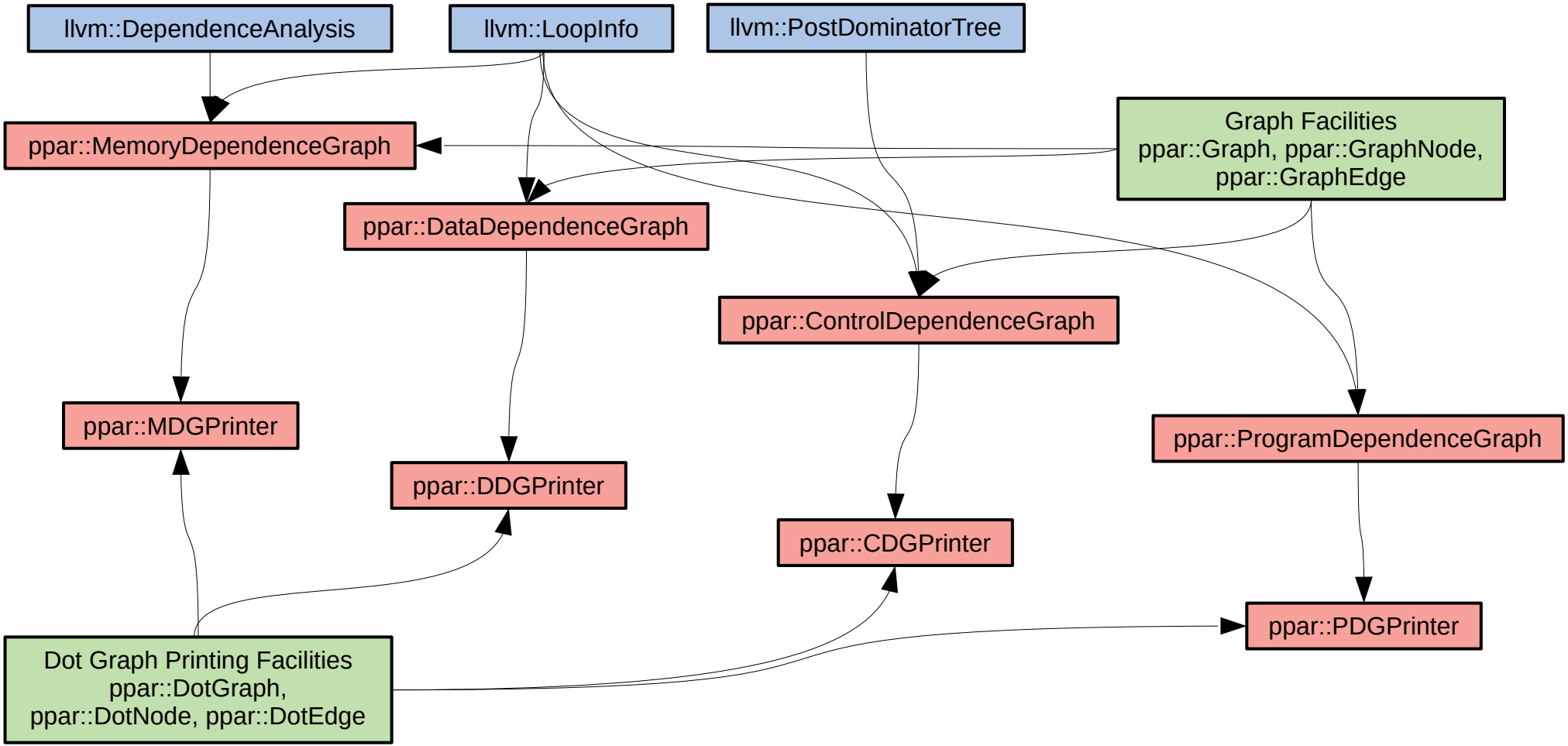
- Add more benchmarks
- Add more metrics
- Derive more results and correlations
- Add machine-learning part
- Integrate into IDE
- If it all shapes into something promising… Make a publication?

GitHub https://github.com/av-maramzin/PParMetrics

Technical details

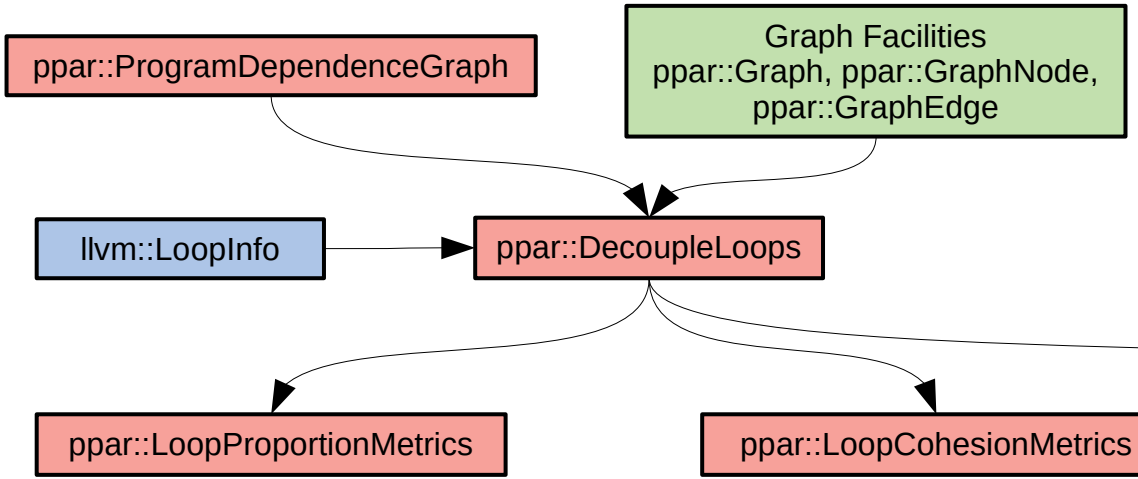
Software Architecture of Graph Building and Printing Facilities

A collection of LLVM passes



Software Architecture of Metrics Collecting Facilities

A collection of LLVM passes



- Loop Absolute Size
- Loop Payload Fraction
- Loop Payload Proper (Critical) SCCs number

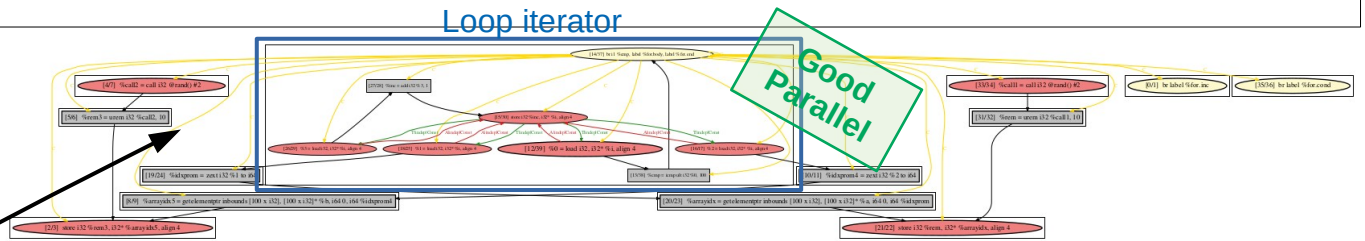
- Iterator Payload Total Cohesion
- Iterator Payload Non-CF Cohesion
- Iterator Payload Mem Cohesion
- Critical Payload Total Cohesion
- Critical Payload Non-CF Cohesion
- Critical Payload Mem Cohesion

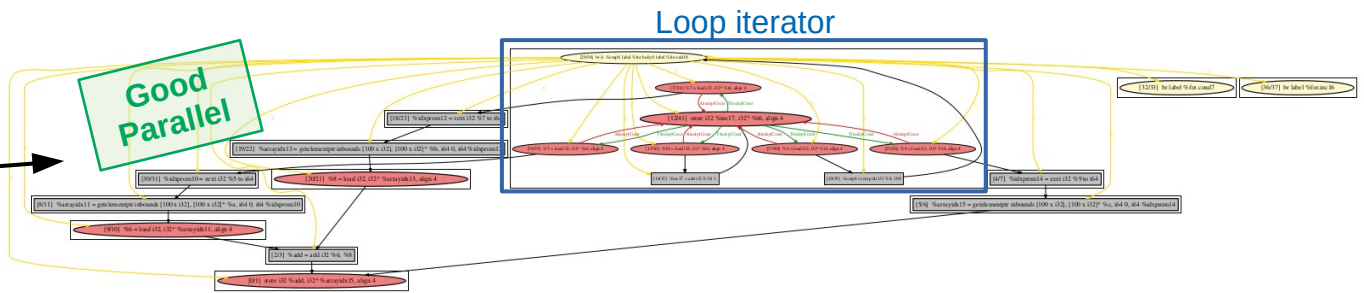
- Payload Dependencies Number (True, Anti, Output)
- Critical Payload Dependencies Number (True, Anti, Output)

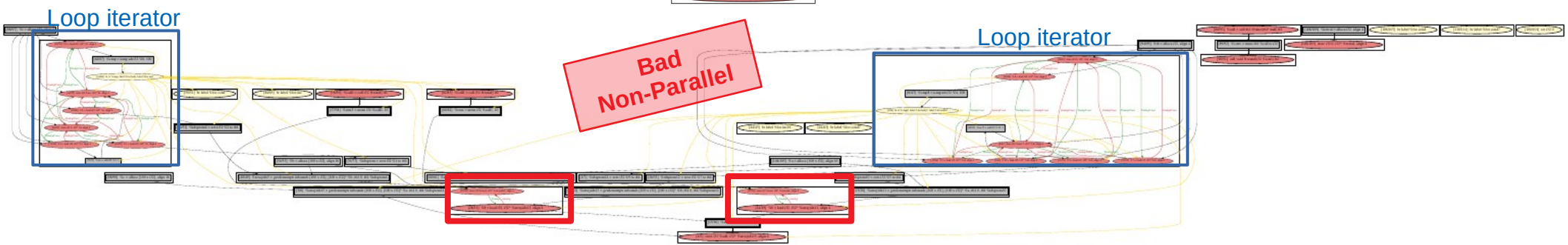
Tool workflow

Tool builds Data Dependence Graph (DDG) + Memory Dependence Graph (MDG) + Control Dependence Graph (CDG) and combines them into = Program Dependence Graph (PDG) for all functions and for all loops inside functions. Then it computes a set of metrics on the built graphs.

```cpp
#include <cstdlib>
#include <ctime>
#include <cmath>

using namespace std;

static const unsigned int size = 100;
static const unsigned int range = 10;

int main() {
    unsigned int a[size];
    unsigned int b[size];
    unsigned int c[size];

    std::srand(std::time(nullptr));

    // initialization loop
    for (unsigned int i = 0; i < size; i++) {
        a[i] = rand() % range;
        b[i] = rand() % range;
    }

    // vector sum computation
    for (unsigned int i = 0; i < size; i++) {
        c[i] = a[i] + b[i];
    }

    return 0;
}
```







Case study [1] : parallelisible loop

```
// vector sum computation
for (unsigned int i = 0; i < size; i++) {
    c[i] = a[i] + b[i];
}
```

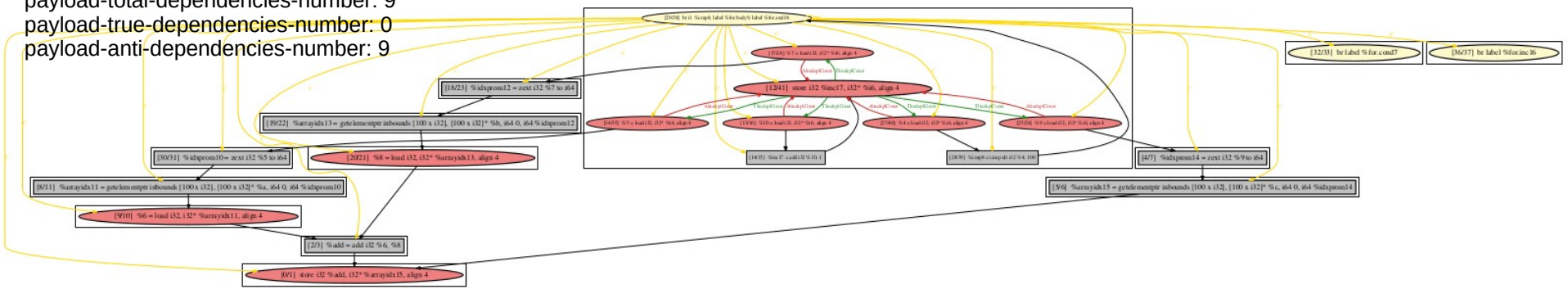
[1] Loop at depth 1 containing: %for.cond7<header><exiting>, %for.body9,%for.inc16<latch>

Loop Proportion Metric Set:
- loop-absolute-size: 21
- Loop-payload-fraction: 57,14 %
- loop-proper-sccs-number: 0

Loop Cohesion Metric Set:
- Iterator-payload-total-cohesion: 31,91 %
- Iterator-payload-non-cf-cohesion: 6.38 %

Loop Dependence Metric Set:
- payload-total-dependencies-number: 9
- payload-true-dependencies-number: 0
- payload-anti-dependencies-number: 9

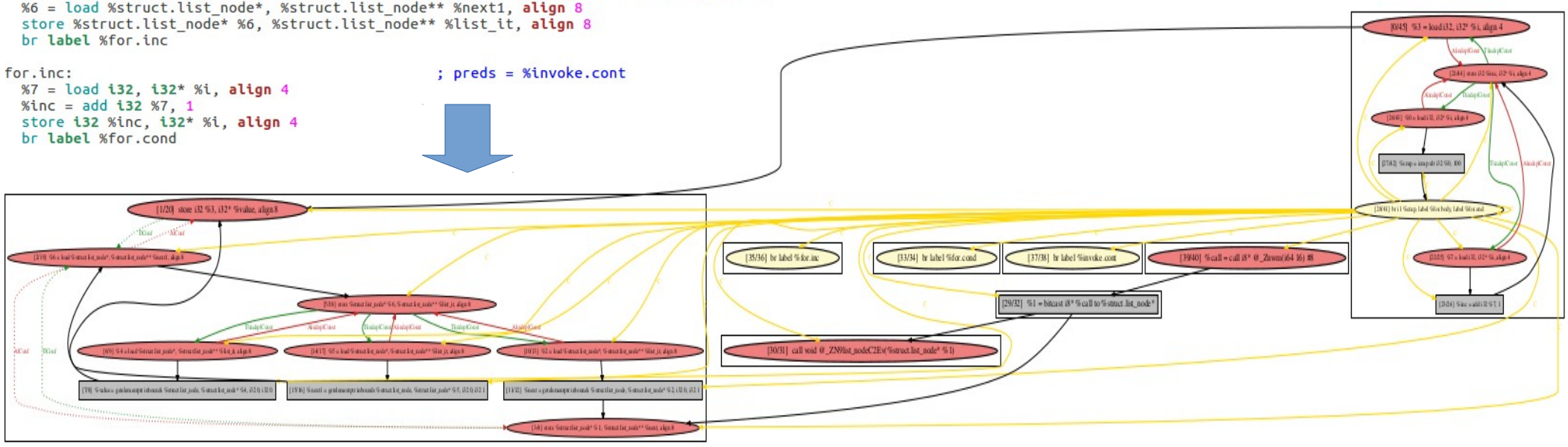
```
for.cond7:                                        ; preds = %for.inc16, %for.end
  %4 = load i32, i32* %i6, align 4
  %cmp8 = icmp ult i32 %4, 100
  br i1 %cmp8, label %for.body9, label %for.end18

for.body9:                                        ; preds = %for.cond7
  %5 = load i32, i32* %i6, align 4
  %idxprom10 = zext i32 %5 to i64
  %arrayidx11 = getelementptr inbounds [100 x i32], [100 x i32]* %a, i64 0, i64 %idxprom10
  %6 = load i32, i32* %arrayidx11, align 4
  %7 = load i32, i32* %i6, align 4
  %idxprom12 = zext i32 %7 to i64
  %arrayidx13 = getelementptr inbounds [100 x i32], [100 x i32]* %b, i64 0, i64 %idxprom12
  %8 = load i32, i32* %arrayidx13, align 4
  %add = add i32 %6, %8
  %9 = load i32, i32* %i6, align 4
  %idxprom14 = zext i32 %9 to i64
  %arrayidx15 = getelementptr inbounds [100 x i32], [100 x i32]* %c, i64 0, i64 %idxprom14
  store i32 %add, i32* %arrayidx15, align 4
  br label %for.inc16

for.inc16:                                        ; preds = %for.body9
  %10 = load i32, i32* %i6, align 4
  %inc17 = add i32 %10, 1
  store i32 %inc17, i32* %i6, align 4
  br label %for.cond7
```



Case study [2] : non-parallelisible loop

```
for.cond:                                         ; preds = %for.inc, %entry
  %0 = load i32, i32* %i, align 4
  %cmp = icmp ult i32 %0, 100
  br i1 %cmp, label %for.body, label %for.end

for.body:                                         ; preds = %for.cond
  %call = call i8* @_Znwm(i64 16) #8
  %1 = bitcast i8* %call to %struct.list_node*
  call void @_ZN9list_nodeC2Ev(%struct.list_node* %1)
  br label %invoke.cont

invoke.cont:                                      ; preds = %for.body
  %2 = load %struct.list_node*, %struct.list_node** %list_it, align 8
  %next = getelementptr inbounds %struct.list_node, %struct.list_node* %2, i32 0, i32 1
  store %struct.list_node* %1, %struct.list_node** %next, align 8
  %3 = load i32, i32* %i, align 4
  %4 = load %struct.list_node*, %struct.list_node** %list_it, align 8
  %value = getelementptr inbounds %struct.list_node, %struct.list_node* %4, i32 0, i32 0
  store i32 %3, i32* %value, align 8
  %5 = load %struct.list_node*, %struct.list_node** %list_it, align 8
  %next1 = getelementptr inbounds %struct.list_node, %struct.list_node* %5, i32 0, i32 1
  %6 = load %struct.list_node*, %struct.list_node** %next1, align 8
  store %struct.list_node* %6, %struct.list_node** %list_it, align 8
  br label %for.inc

for.inc:                                          ; preds = %invoke.cont
  %7 = load i32, i32* %i, align 4
  %inc = add i32 %7, 1
  store i32 %inc, i32* %i, align 4
  br label %for.cond
```

```
list_node_t begin;
list_node_t* list_it;

list_it = &begin;
for (unsigned int i = 1; i < size; i++) {

    list_it->next = new list_node_t;


    list_it->value = i;


    list_it = list_it->next;
}
```



Case study [2] : non-parallelisible loop

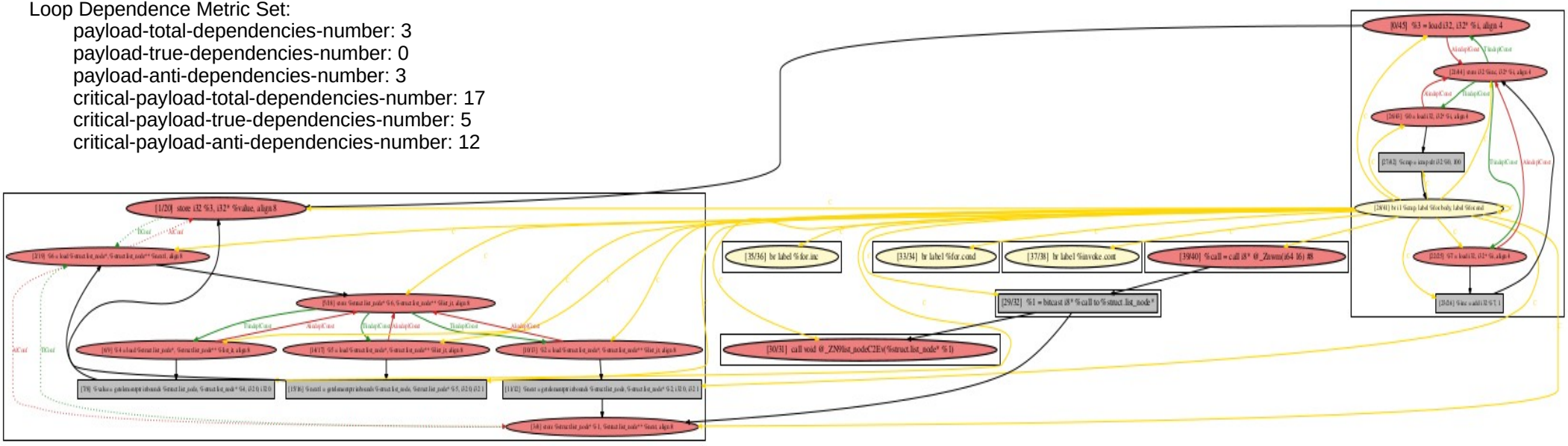
[3] Loop at depth 1 containing: %for.cond<header><exiting>,%for.body, %invoke.cont,%for.inc<latch>

Loop Proportion Metric Set:
- loop-absolute-size: 23
- Loop-payload-fraction: 69,57 %
- loop-proper-sccs-number: 1

Loop Cohesion Metric Set:
- Iterator-payload-total-cohesion: 31,48 %
- Iterator-payload-non-cf-cohesion: 1.85%
- Iterator-payload-mem-cohesion: 0 %
- Critical-payload-total-cohesion: 5 %
- Critical-payload-non-cf-cohesion: 5 %
- critical-payload-mem-cohesion: 0

Loop Dependence Metric Set:
- payload-total-dependencies-number: 3
- payload-true-dependencies-number: 0
- payload-anti-dependencies-number: 3
- critical-payload-total-dependencies-number: 17
- critical-payload-true-dependencies-number: 5
- critical-payload-anti-dependencies-number: 12

```
list_node_t begin;
list_node_t* list_it;

list_it = &begin;
for (unsigned int i = 1; i < size; i++) {

    list_it->next = new list_node_t;


    list_it->value = i;


    list_it = list_it->next;
}
```

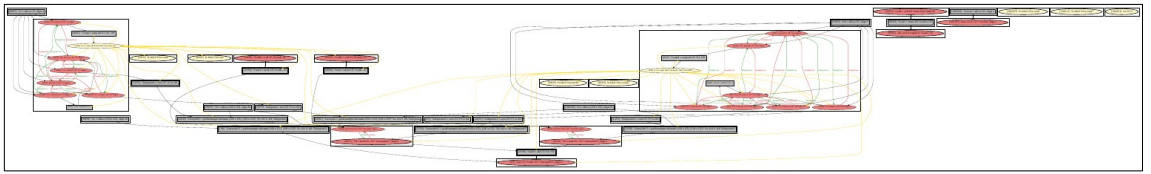


Backup slides

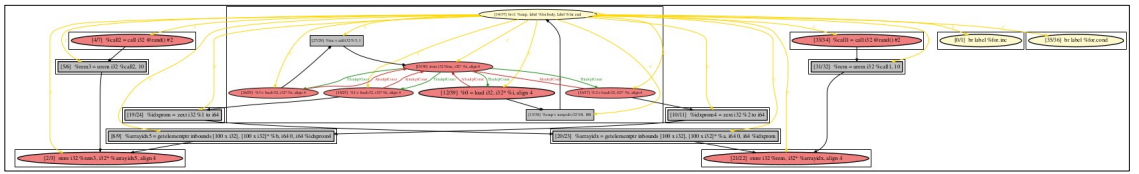
Basic idea

```cpp
#include <cstdlib>
#include <ctime>
#include <cmath>

using namespace std;

static const unsigned int size = 100;
static const unsigned int range = 10;

int main() {
    unsigned int a[size];
    unsigned int b[size];
    unsigned int c[size];

    std::srand(std::time(nullptr));

    // initialization loop
    for (unsigned int i = 0; i < size; i++) {
        a[i] = rand() % range;
        b[i] = rand() % range;
    }

    // vector sum computation
    for (unsigned int i = 0; i < size; i++) {
        c[i] = a[i] + b[i];
    }

    return 0;
}
```

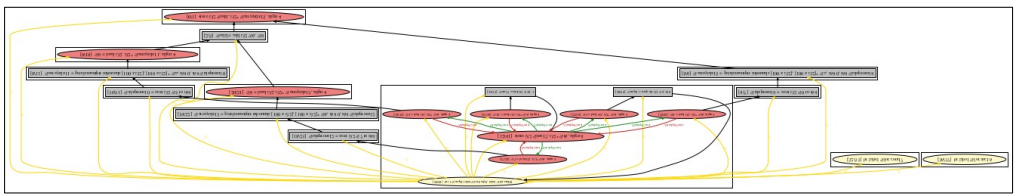
Function PDG



Loop0 PDG



Loop1 PDG



llvm::DependenceAnalysis

- LLVM pass which analyses dependencies between memory accesses. As of LLVM 6.0 it is an implementation of the approach described in [1].
- llvm::DependenceAnalysis pass exists to support llvm::DependenceGraph pass (*does not exist in LLVM yet*).
- There are two separate passes, because it is a useful separation of concerns. A dependence exists if two conditions are met:
  1) Two instructions reference the same memory location
  2) There is a flow of control, leading from one instruction to the other.
- llvm::DependenceAnalysis addresses the first condition, llvm::DependenceGraph (*not available as a standard LLVM pass yet, as of LLVM 6.0*) addresses the second.
- llvm::DependenceAnalysis is *Work In Progress* in LLVM

[1] Practical Dependence Testing. Gina Goff, Ken Kennedy, Chau-Wen Tseng. Department of Computer Science, Rice University, Houston, TX. Proceedings of the ACM SIGPLAN ‘91 Conference on Programming Language Design and Implementation. Toronto, Ontario, Canada, June 26-28, 1991.

llvm::DependenceAnalysis

- LLVM class Dependence represents a dependence between two memory references in a function.

```
class Dependence {
  Dependence(Instruction *Source,
             Instruction *Destination);

  bool isInput() const;
  bool isOutput() const;
  bool isFlow() const;
  bool isAnti() const;
  bool isOrdered() const { return isOutput() || isFlow() || isAnti(); }
  bool isUnordered() const { return isInput(); }

  /// isLoopIndependent - should be set by the caller if it appears that control flow can reach
  /// from Src to Dst without traversing a loop back edge.
  virtual bool isLoopIndependent() const { return true; }
  /// isConfused - Returns true if this dependence is confused
  /// (the compiler understands nothing and makes worst-case assumptions).
  virtual bool isConfused() const { return true; }
  /// isConsistent - Returns true if this dependence is consistent
  /// (occurs every time the source and destination are executed).
  virtual bool isConsistent() const { return false; }
  /// getLevels - Returns the number of common loops surrounding the
  /// source and destination of the dependence.
  virtual unsigned getLevels() const { return 0; }
  /// getDirection - Returns the direction associated with a particular level.
  virtual unsigned getDirection(unsigned Level) const { return DVEntry::ALL; }
  /// getDistance - Returns the distance (or NULL) associated with a particular level.
  virtual const SCEV *getDistance(unsigned Level) const { return nullptr; }
  /// isPeelFirst - Returns true if peeling the first iteration from this loop will break this dependence.
  virtual bool isPeelFirst(unsigned Level) const { return false; }
  /// isPeelLast - Returns true if peeling the last iteration from this loop will break this dependence.
  virtual bool isPeelLast(unsigned Level) const { return false; }
  /// isSplitable - Returns true if splitting this loop will break the dependence.
  virtual bool isSplitable(unsigned Level) const { return false; }
  /// isScalar - Returns true if a particular level is scalar; that is, if no subscript in the source or
  /// destination mention the induction variable associated with the loop at this level.
  virtual bool isScalar(unsigned Level) const;
};
```

llvm::DependenceGraph

Not yet ready in LLVM!
Work In Progress!

- Generally, the dependence analyzer will be used to build a dependence graph for a function. Looking for cycles in the graph shows us loops, that cannot be trivially vectorized/parallelized

- We can try to improve the situation by examining all the dependences that make up the cycle, looking for ones we can break. Sometimes, peeling the first or last iteration of a loop will break dependences, and there are flags for those possibilities. Sometimes, splitting a loop at some other iteration will do the trick, and we've got a flag for that case. Rather than waste the space to record the exact iteration (since we rarely know), we provide a method that calculates the iteration. It's a drag that it must work from scratch, but wonderful in that it's possible.

  Here's an example:

```
for (i = 0; i < 10; i++)
        A[i] = ...
        ... = A[11 – i]
```

  There's a loop-carried flow dependence from the store to the load, found by the weak-crossing SIV test. The dependence will have a flag, indicating that the dependence can be broken by splitting the loop. Calling getSplitIteration will return 5. Splitting the loop breaks the dependence, like so:

```
for (i = 0; i <= 5; i++)
    A[i] = ...
    ... = A[11 - i]
for (i = 6; i < 10; i++)
    A[i] = ...
    ... = A[11 - i]
```

  breaks the dependence and allows us to vectorize/parallelize both loops.

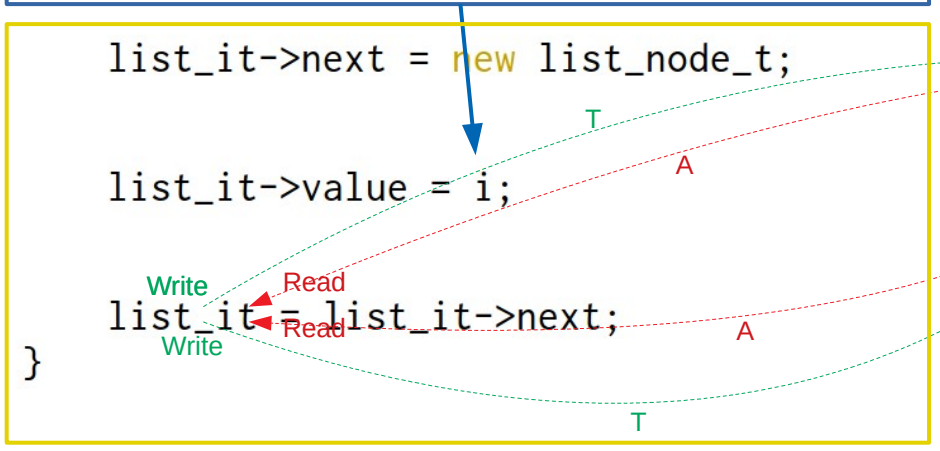
Case study [2] : non-parallelisible loop

```
list_node_t begin;
list_node_t* list_it;

list_it = &begin;
for (unsigned int i = 1; i < size; i++) {
    list_it->next = new list_node_t;

    list_it->value = i;

    list_it = list_it->next;
}
```

Iterator

Payload

```
list_node_t begin;
list_node_t* list_it;

list_it = &begin;
for (unsigned int i = 1; i < size; i++) {
    list_it->next = new list_node_t;

    list_it->value = i;

    list_it = list_it->next;
}
```



General work observation

- To judge about true program parallelisability, we have to disassemble the program (its program dependence graph) to the smallest finest-grain pieces
- As it appears at the moment, the true indicator of the loop parallelisability is the absence of strongly connected components (besides the iterator one) of the size, greater than 1 instruction: there are cycles present in such strongly connected components, which imply dependence between instructions tying up/entangling loops and preventing them from parallelisation
- According to code comments, there is a work going on in LLVM on building llvm::DependenceGraph and breaking its edges with loop splitting and peeling.