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DITTANY: Strength-Based Dynamic Information Flow Analysis Tool for x86 Binaries

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Abstract—Dynamic dependence analysis monitors information flow between instructions in a program at runtime. Strength-based dynamic dependence analysis quantifies the strength of each dependence chain by a measure computed based on the values induced at the source and target of the chain. To the best of our knowledge, there is currently no tool available that implements strength-based dynamic information flow analysis for x86.

This paper presents DITTANY, tool support for strength-based dynamic dependence analysis and experimental evidence of its effectiveness on the x86 platform. It involves two main components: 1) a Pin-based profiler that identifies dynamic dependences in a binary executable and records the associated values induced at their sources and targets, and 2) an analysis tool that computes the strengths of the identified dependences using information theoretic and statistical metrics applied on their associated values. We also study the relation between dynamic dependences and measurable information flow, and the usage of zero strength flows to enhance performance.

DITTANY is a building block that can be used in different contexts. We show its usage in data value and indirect branch predictions. Future work will use it in countermeasures against transient execution attacks and in the context of approximate computing.

Keywords—binary analysis, dynamic information flow analysis, dynamic slicing, information flow strength, data value prediction, indirect branch prediction.

I. INTRODUCTION

Information flow analysis is a technique that analyzes the flow of information between program objects during execution. It has a wide variety of applications that range from making systems more secure by tracking the dissemination of data inside a system and ensuring some security properties, to helping developers and analysts better understand the code that systems are executing. There exist two types of information flow: static [11], [13], [39] and dynamic [16]. We hereby consider dynamic information flow analysis.

Information flow between objects in a program is crucial to its security since it might reveal tampering or leakage of sensitive information. Security policies can specify the set of objects between which information can flow in a program. Information flow is also important in testing, debugging and maintenance of programs.

In this paper, we present DITTANY, a strength-based dynamic information flow analysis (DIFA) tool that instruments x86 binaries and does not require the availability of the source code. The tool is intended to be generic in a manner to allow several techniques to make use of it. By default, the tool obtains the dependences between all instructions; however, the user can selectively specify which instructions to consider based on their types, instruction pointer (IP), and/or the routines that include them. The tool provides several other options for the user such as considering data dependence only or both data and control dependences. The tool also computes the strengths of the identified dependences. It quantifies information flow in a non-binary manner, and distinguishes between linear and non-linear association, which enables its usage in non-traditional applications such as approximate computing. To the best of our knowledge, currently there is no tool that accomplishes the previously mentioned roles.

DITTANY is a building block that can be used in different contexts. We show its usage in data value and indirect branch predictions. We will use it in future work in countermeasures against transient execution attacks and in the context of approximate computing.

In this paper, we make the following contributions:

- We build a Pin-based dynamic information flow analysis tool that identifies dynamic dependences in a binary executable and records the associated values induced at their sources and targets (Sections IV and VI-A).
- We present an analysis tool that computes the strengths of the identified dependences using information theoretic and statistical metrics applied on their associated values (Sections V and VI-B).
- We use normalized mutual information to identify maximum flow of information from source to target (Section V-A3), show that the existence of data dependence from a source to a target instruction is not a sufficient condition for the flow of information from the source to the target (Sections VII-A and VII-B), and shed light on
exploiting paths that have zero strength flow to increase the effective instruction level parallelism (Section VII-C).

- We introduce dynamic information flow analysis as a tool to study the nature of data and control correlations in programs and to improve the accuracy of instructions outcomes prediction. We present the potential usage of the proposed tool for data value and indirect branch predictions (Section VIII).

II. BACKGROUND

A. Information Flow

Information flows from a source object \( x \) to a target object \( y \) whenever information stored in \( x \) is passed directly or indirectly to object \( y \) [13]. A given program statement designates a specific flow \( f \) if executing the statement could result in the flow \( f \). Flows can be either direct or indirect. Direct information flow is due to the propagation of information as a result of data dependence. Source variable is directly involved in the computation of the target variable value. The occurrence of a direct flow is independent of the value of its source object. Assignment, I/O statements, and value-returning procedure calls are examples of statements that result in direct flow. Indirect information flow is due to control dependence. Source object indirectly affects the value of the target object. A statement \( t \) is data-dependent on a statement \( s \) if \( t \) uses a variable that is defined in \( s \). A statement \( t \) is control-dependent on a statement \( s \) if \( s \) decides via branches it controls whether \( t \) is executed or not [17], [33], [34].

B. Program Slicing

A program slice is the set of program statements that may affect the values at some point of interest. A static slice is a set of program statements which may affect the value assigned to a variable \( v \) at a specific statement \( S \). A dynamic slice is a set of program statements that actually affect the value assigned to a variable \( v \) at a specific statement \( S \) for a particular execution of the program. We define an assembly dynamic slice (ADS) as the set of assembly instructions that actually affect the value assigned to a register or memory location at a specific instruction \( ins \) for a particular execution of the program.

C. Indirect Branch Prediction

An indirect branch specifies where the address of the next instruction to execute is located, rather than specifying the address itself, as in a direct branch. Indirect branches can depend on the value of a register or memory location. The target address is not known until the instruction is executed. A single indirect branch can have multiple targets.

Indirect branches implement common programming constructs such as switch statements, virtual function calls and calls through function pointers. Correctly predicting the target addresses of indirect branches can significantly enhance the performance of programs that make a lot of use of the programming features that result in indirect branches.

Most existing indirect branch prediction techniques can be classified as either history-based [9], [14], [15], [23], [29], [24] or precomputation-based [37].

History-based techniques predict the target of an indirect instruction based on its previous history and/or history of previously executed indirect branch instructions. The branch target buffer (BTB) is used to predict the target of the branch as the last taken target [28]. This works well for branches that usually jump to the same target, which are often known as monomorphic indirect branches. However in the case of indirect branches which jump to many different targets, known as polymorphic indirect branches, the prediction accuracy is usually poor.

In this paper, we present a simple profiling-based correlation indirect branch prediction technique that employs dynamic information flow analysis.

D. Value Prediction

Value prediction [30], [32], [48] is a technique to increase parallelism by attempting to overcome serialization constraints caused by true data dependences. By predicting the outcome of an instruction before it executes, value prediction allows data dependent instructions to issue and execute speculatively, hence increasing parallelism when the prediction is correct. In case of a misprediction, the execution is redone with the corrected value. If the benefit from increased parallelism outweighs the misprediction recovery penalty, overall performance could be improved. Enhancing performance with value prediction therefore requires highly accurate prediction methods. Most existing general value prediction techniques are local, i.e., future outputs of an instruction are predicted based on outputs from previous executions of the same instruction. Local value prediction methods can be either computational or context based [48]. A computational predictor yields a predicted next value by performing an operation on previous values such as last value (LV) predictor [32] and stride value (STR) predictor [49]. A 2-δ stride predictor keeps track of two stride values \( s_1 \) and \( s_2 \) [35]. A context based predictor makes value prediction based on its observation of previous patterns. An order \( k \) Finite Context Method (FCM) predictor uses \( k \) preceding values [40]. Differential Finite Context Method (DFCM) hashes recent history of strides rather than values and looks up a stride in the hashtable to make a prediction. DFCM has the potential to be more space efficient and faster to warm up than FCM [6].

III. RELATED WORK

Lampson initiated the research on information flow analysis and listed a number of possible information leaks [27]. Fenton introduced an abstract machine, named Data Mark Machine, that supports dynamic checking of information flows [16]. Jones and Lipton presented a similar mechanism [22]. Zimmerman et al. showed an intrusion detection model that employs runtime enforcement of an information flow policy that dictates which information flows are allowable in a given system [53], [52]. Their model focus on information flow between entire objects. Haldar et al. extended the Java Virtual Machine (JVM) to enforce information flow policies at the granularity of objects without considering control dependences [21].

Static information flow analysis techniques are less precise than dynamic techniques since they consider all control flows as executable [13].
Algorithm 1: Data dependence analysis

1. Get the sets of dependences of the source operands;
2. Unify the sets obtained in step 1;
3. Unify the set obtained in step 2 with the address of the executed instruction;
4. Clear the dependence sets of the target operands and assign to it the set obtained in step 3;
5. Set the dependence set of the executed instruction to its union with the set obtained in step 2;

Program slicing was originally introduced by Weiser [47] who proposed the first static slicing algorithm to help debugging programs. Afterward, Korel and Laski [25] proposed dynamic slicing that considers runtime information when selecting the set of statements that affects a specific program variable. The previously mentioned algorithms use backward analysis, which requires the a priori availability of the execution trace. Korel and Yalamanchili were the first to propose a forward-computing algorithm for dynamic slicing [26]. Tip [42] presented a survey of both static and dynamic program slicing techniques. Program slicing has been explored for Web applications [31], [43], [36] and for Android [51], [50], [5], [2].

DynFlow is a tool that supports strength-based dependence analysis of Java programs [45]. It calculates flow strength at the bytecode level whereas we are interested in obtaining the results the tool provides at the assembly level for C and C++ programs. Forward computing dynamic slicing and information flow analysis algorithms, which we use in this paper, do not need the a priori availability of the execution trace.

IV. DYNAMIC DEPENDENCE IMPLEMENTATION

In this section, we describe our approach to dynamic dependence analysis.

A. Data Dependence Analysis

We define instruction target operands as the instruction destination operand and any implicit operand whose value might change when the instruction executes and instruction source operands as the explicit and/or implicit source operands of the instruction. We also define a mapping function to each instruction opcode. After the dynamic execution of each assembly instruction, we calculate the assembly dynamic slice of the target operands, by using instruction-type related mapping function that takes as inputs the assembly dynamic slices of the source operands of the instruction. The instruction itself is added to the dynamic slices of its target operands. The new set of dependences of the executed instruction is obtained as the union of its existing set with those of its source operands. Algorithm 1 summarizes the steps.

We mean by unify the union operation of two or more sets. In set theory, the union of a collection of sets is the set of all elements in the collection. According to the opcode of the executed instruction, we identify the set of source and the set of target operands. We obtain the set of dependences of each of the source operands and unify the obtained set of dependences. We name the obtained set SourceDepSet. We unify SourceDepSet with the address of the executed instruction and assign the result to a set that we name DepSet. We clear the dependence sets of the target operands and assign to it DepSet. We set the dependence set of the executed instruction to its union with SourceDepSet.

B. Control Dependence Analysis

A Control Flow Graph (CFG) is a directed graph augmented with two special nodes entry and exit with no predecessors and no successors, respectively. A node of the graph corresponds to a basic block, i.e., a single-entry single-exit sequence of instructions, while an edge represents the potential flow of control from one basic block to another, branches or fall-through execution. A CFG node $n$ post-dominates another node $m$ ($n$ postdom $m$ or $n$ postdom $(m) = n$) if every path from $m$ to exit goes through $n$. Node $n$ is the immediate post-dominator of node $m$ ($n$ ipdom $m$ or $n$ ipdom $(m) = n$) iff $m \neq n$; $n$ ipdom $m$; $\forall d \neq m, d$ ipdom $m \rightarrow d$ ipdom $n$. Every node has a unique immediate post-dominator.

A node $n$ of a CFG is control-dependent on a node $c$ if (1) there exists an edge $c_1$ coming out of $c$ that definitely causes $n$ to execute, and (2) there exists some edge $c_2$ coming out of $c$ that is the start of some path that avoids the execution of $n$. The decision made at $c$ affects whether $n$ gets executed. Formally, $n$ is control-dependent on $c$ if: (1) $n \neq c$, (2) $n$ does not post-dominate $c$, and (3) there exists a path from $c$ to $n$ such that $n$ post-dominates every node in the path except $c$ [3], [4], [17].

To track control flow-based dependences, we use an approach similar to the one originated in [44], [45]. The outcome of a conditional branch dictates whether the instructions that depend on it are executed or not. The values of operands that affect the branch outcome may affect the dependent instructions target operands values. Thus, we need to add the set of dependences of the source operands of the branch instruction to the set of dependences of the targets operands of the branch dependent instructions. To achieve this, we leverage dynamic slicing and static post-dominance information using Algorithm 2.

The algorithm uses a stack, denoted controlDepStack, which holds pointers to branch instructions whose dynamic control scope is still active. The dynamic control scope of a branch instruction terminates when its ipdom is executed, at
which time, the branch instruction is popped off controlDepStack. To ensure that the stack size is bounded, when a newly encountered branch instruction has the same ipdom as that of the branch instruction at the top of the stack controlDepStack, denoted TOS, we pop TOS off controlDepStack. This is acceptable as explained in [45].

C. Recording Values

We determine the assembly dynamic slices for selected or all executed instructions in a program. We are interested in quantifying the amount of flow from a source instruction to a target instruction. To achieve this for non-branch source instructions, we first need to log pairs of values corresponding to consecutive dynamic executions of both instructions. When the source of a flow is a branch, we store the status of the branch, taken or non-taken, for each occurrence of the flow.

We use a map structure to associate with each instruction the outcome of its last execution. We create a ValuePairs class that holds pair of values corresponding to consecutive dynamic execution of source and target instructions. We create another class, Depend, that is instantiated for each pair of dependent instructions – dependence does not have to be strictly between distinct instructions, it can be from the instruction to itself. After the dynamic execution of each instruction, we update its corresponding Depend instance with pairs of values of its last outcome and the last outcomes of instructions on which it depends during its current execution. In fact, the dependences of an instruction may change from an execution to another.

V. Dependence Strength

Informally, information flow occurs from an instruction ins1 to an instruction ins2 during execution of a program if observing the outcome of ins2 at some point reduces one’s uncertainty about the outcome of ins1 at an earlier point, which indicates that ins2 is probabilistically dependent on ins1. The strength of dependences measures the amount of information they propagate. We follow an approach similar to [46] to calculate the strength of dependences.

We use three techniques to measure information flow strength. The first employs entropy, conditional entropy and mutual information. The other two are correlation-based; one employs standard r and the other, eta coefficient. Standard r measures linear relations only; however, information theoretic and eta coefficient measure both linear and non-linear relations. Therefore, we can identify and separate linear and non-linear correlations.

A. Entropy-Based Technique

1) Entropy: Entropy is a measure of the uncertainty of a random variable. It explicitly quantifies the information content in a given source of data. The entropy of a discrete random variable X is defined as [12]:

\[
H(X) = - \sum_i P(X = x_i) \log_2 P(X = x_i).
\]

Conditional entropy of a random variable X, given that the random variable Y is known, measures the remaining uncertainty about the value of X after knowing the value of Y. It is defined as:

\[
H(X|Y) = - \sum_j P(Y = y_j) \times \sum_i P(X = x_i|Y = y_j) \log_2 P(X = x_i|Y = y_j).
\]

\[
H(X|Y) = 0 \text{ if and only if the value of } X \text{ is completely determined by the value of } Y. \text{ } H(X|Y) = H(X) \text{ if and only if } X \text{ and } Y \text{ are independent random variables.}
\]

2) Mutual Information: Mutual information is a measure of the amount of information one random variable contains about another. The mutual information between two discrete random variables X and Y is given by:

\[
I(X;Y) = H(X) - H(X|Y) = H(Y) - H(Y|X) = H(x) + H(Y) - H(X,Y),
\]

where H(X,Y) is the joint entropy. Mutual information is always non-negative. The mutual information I(X;Y) is the reduction in the uncertainty of X due to the knowledge of Y. Mutual information is symmetric, I(X;Y) = I(Y;X). Thus X says as much about Y as Y says about X.

Mutual information can detect arbitrary non-linear relationships between X and Y. I(X;Y) can be normalized to a value between 0 and 1:

\[
NMI(X;Y) = \frac{H(X) - H(X|Y)}{H(X)} = \frac{H(Y) - H(Y|X)}{H(Y)}
\]

\[
NMI(X;Y) = \begin{cases} 1 & \text{for } H(X|Y) = 0, \\ 0 & \text{for } H(X|Y) = H(X). \\ \end{cases}
\]

3) Entropy-Based Strength of Flow: Following the analysis presented in [46], the amount of information transferred from x (in state σ) to y (in state τ) is:

\[
\text{StrengthFlow}_{\text{Entropy}}(x,y) = H(X_\sigma) - H(X_\sigma|Y_\tau)
\]

\[
\text{StrengthFlow}_{\text{Entropy}}(x,y) \text{ will be zero if no measurable flow occurred between } x \text{ and } y, \text{ and it will be greater than zero otherwise. The value that results from this equation does not have a range limit.}
\]

We employ normalized mutual information as a technique to measure the strength of flow, since it results in a value between 0 and 1, where 0 indicates no flow of information, and 1 indicates maximum flow of information. Maximum flow of information implies that if the value of the source variable is known, we can definitely deduce the value of the target variable (no uncertainty remains about the value of the target variable knowing the value of the source variable).

\[
\text{Normalized Mutual Information} = \frac{H(X_\sigma) - H(X_\sigma|Y_\tau)}{H(X_\sigma)}
\]

\[
\text{Normalized mutual information allows us to identify cases where there is maximum flow of information from source}
\]
to target. Previous work [46] only reasons about weak and strong flow, with no additional interpretation of the values obtained for measured strengths of flows. Moreover, it does not provide a criteria to classify a strength of flow (either weak or strong), and does not address the issue of maximum flow of information.

B. Correlation-Based Techniques

We now provide some information about correlation-based strength of flow techniques we use in our tool.

1) Standard $r$: The Pearson product moment correlation coefficient, which is also known as Pearson’s $r$ or standard $r$, measures the strength of the correlation (linear dependence) between two variables. It ranges between $-1$ and $+1$ and is defined as [38]:

$$r = \frac{Cov(x,y)}{\sigma_x \sigma_y}$$

where $Cov(x,y)$ is the covariance of $x$ and $y$, $\sigma_x$ is the standard deviation of $x$, and $\sigma_y$ is the standard deviation of $y$. $r^2$ is called the coefficient of determination or proportion of explained variance.

When two variables have a nonlinear relationship, standard $r$ will underestimate the strength of the relationship. $StrengthFlow_{r}(x,y)$ is the absolute value of standard $r$.

2) Eta Coefficient: The correlation ratio or eta coefficient provides the same value as standard $r$ for linearly related variables and a greater value for non-linearly related variables. The difference between eta and $r$ presents a measure of the non-linearity of the relation between two variables. The eta coefficient is defined as:

$$\eta = \frac{\sigma\overline{y}}{\sigma_y}$$

where $\overline{y}$ is the mean of the category that $y$ belongs to, $\sigma\overline{y}$ is the standard deviation of $\overline{y}$, and $\sigma_y$ is the standard deviation of $y$ [41], [10].

In the case that either $x$ or $y$ is constant, $StrengthFlow_{\eta}(x,y)$ is defined to be zero, because there is no linear association between $x$ and $y$. Similarly, in the case that $y$ is constant, $StrengthFlow_{\eta}(x,y)$ is defined to be zero, because there is no linear or nonlinear association between the variables.

VI. DITTANY

We implement our approach to dynamic dependence analysis in a tool that we call DITTANY\(^1\). The tool leverages Pin dynamic instrumentation tool.

A. Information Flow Analysis

Figure 1 presents an overview of DITTANY mode of operation for dynamic information flow analysis. By default, the tool tracks flow of information among all dynamically executed instructions. We provide several command line options that enable the user to obtain flow of information along data dependences only or along both data and control dependences, select a particular routine to instrument, specify the routine at which instrumentation starts and the routine at which it terminates, indicate the number of instructions to skip before starting instrumentation, choose a particular path of interest, mention an upper limit on the number of instructions to instrument, etc.

When the user specifies the types of instructions to instrument, Step 5 of Algorithm 1 is only executed for the specified instructions. For non-specified instructions, Step 3 of Algorithm 2 only updates their target operands without updating their sets of dependences. Taking into consideration the user selection, the tool instrument the input executable which is run to produce profiles that capture the induced information flows along with their respective source and target values.

B. Strength Calculation

Figure 2 presents an overview of DITTANY mode of operation for the strength of flow computation. We parse the information flows obtained to determine source and target instructions, and calculate the strength of flow from source to target using information theory, standard $r$ and eta coefficient. The tool also identifies instructions which outcomes are constant during all executions. The flows can be categorized according to their strength using one or more of the used strength measuring schemes.

VII. DYNAMIC DEPENDENCE AND INFORMATION FLOW

We address in this section the relation between dependences and measurable information flow, and the usage of zero strength flows to enhance performance. The work explored in Sections VII-A and VII-B below, was addressed in different context in [46].

A. Dependences and Measurable Information Flow

We answer in this section the following question: Are dynamic dependences generally indicative of measurable information flow?

\(^{\text{1}}\)Dittany can refer to three different plants: White Dittany (Dictamnus Albus), Dittany of Crete (Origanum Dictamnus), and Common Dittany (Cunila Mariana). DITTANY: Dynamic Information and TainTing flow ANAlYsis tool. We have implemented the strength based information flow analysis phase, and we still have the tainting part.
Consider Listing 1 and its corresponding assembly code Listing 2. It represents a for loop that contains two statements. The first statement assigns to a variable \( a \) the result of the subtraction of \( x \) modulus 5 from \( x \). The second statement assigns \( a + 1 \) to variable \( y \).

The outcomes of the instructions labeled \( \text{ins1} \), \( \text{ins2} \) and \( \text{ins3} \) correspond to the values of \( x \), \( a \), and \( y \) in the source code respectively. Both instructions \( \text{ins2} \) and \( \text{ins3} \) are data-dependent on instruction \( \text{ins1} \). Instruction \( \text{ins3} \) is data-dependent on instruction \( \text{ins2} \).

When executing the program, the following (\( \text{ins1}, \text{ins2}, \text{ins3} \)) value triplets result:

\[
\{(0, 0, 1), (1, 0, 1), (2, 0, 1), (3, 0, 1), (4, 0, 1), (5, 5, 6), (6, 5, 6), (7, 5, 6), (8, 5, 6), (9, 5, 6), (10, 10, 11), (11, 10, 11), (12, 10, 11), (13, 10, 11), (14, 10, 11), (15, 15, 16), (16, 15, 16), (17, 15, 16), (18, 15, 16), (19, 15, 16)\}
\]

Computing the strength of flows (\( \text{ins1}, \text{ins2} \), \( \text{ins1}, \text{ins3} \)) and (\( \text{ins2}, \text{ins3} \)) using normalized mutual information yields 0.46, 0.46 and 1.0 respectively. The low value of the strength of flow (\( \text{ins1}, \text{ins2} \)) is expected since by learning that the outcome of \( \text{ins2} \) is 0, an observer is not certain of the outcome of \( \text{ins1} \), which could be 0, 1, 2, 3 or 4. Similarly for the strength of flow (\( \text{ins1}, \text{ins3} \)). The strong value of the strength of flow (\( \text{ins2}, \text{ins3} \)) is justified by the fact that learning the outcome of \( \text{ins3} \), we can infer the outcome of \( \text{ins2} \) with 100% certainty.

Listing 3 is another example with its corresponding assembly code Listing 4. The only difference between this example and the previous one is the usage of multiplication instead of modulus. Computing the strength of flows (\( \text{ins1}, \text{ins2} \), \( \text{ins1}, \text{ins3} \) and (\( \text{ins2}, \text{ins3} \)) using normalized mutual information yields 1.0 for all of them.

We can conclude from the above two examples that the presence of dynamic dependence between two instructions is not a sufficient condition for the strong flow of information between them. Other program constructs and constraints are beyond the scope of this paper.

### B. Zero Strength Flows Interpretations and Analyses

Zero strength flows are dependences where there is no correlation between the values of the source and those of the target. The strength of a zero strength flow measured using \( \eta \) coefficient, normalized mutual information and standard \( r \) equals to 0.

We evaluate our metrics on the SPEC CINT2006, i.e., SPEC CPU 2006 integer benchmarks [1] described in Table III in Appendix. We use all CINT2006 benchmarks except bzip2 due to a bug.

We define self flow as the flow from and instruction into itself. Figure 3 shows that Self Zero Strength \( r \), Self Zero Strength ETA and Self Zero Strength Entropy accounts for
C. Zero Strength Flows and Instruction Level Parallelism

In this section, we answer the following question: Can we exploit paths that have zero strength flow to increase the effective instruction level parallelism (ILP)?

To answer this question, we do the following: (1) use DITTANY to identify the apparent information flows that occurred during the execution of several programs, (2) compute the strength of the identified flows, i.e., measure the amount of information they propagated, (3) select zero strength flows between distinct instructions where the source of flows are load instructions, and (4) analyze the predictability of the values of the source and the target of the selected flows.

For SPEC CPU 2006 integer benchmarks [1], we measure the prediction accuracy and coverage of the source and the target of flows using last value [32], 2-δ stride [35] and DFCM [6] predictors. Prediction accuracy is the number of successful predictions over the total number of attempted predictions. Prediction coverage is the number of an instruction predictions over the total number of an instruction updates.

Figure 5 shows that the target instructions are predictable on average with 100%, 95.477% and 97.455% accuracies using last value, 2-δ stride and DFCM predictors respectively. The prediction coverages achieved on average using last value, 2-δ stride and DFCM predictors are 67.2%, 70.53% and 86.77% respectively.

Figure 6 shows that 40.04% of the selected source load instructions are selected for confident predictions, and 86% of the selected target instructions are selected for confident predictions. We use confidence counters to guide when to use the prediction information.

Figure 7 shows that the selected load instructions and target instructions account on average for 0.705% and 3.58% respectively of the total number of dynamically executed instructions.

We can conclude from our results that 86% of the target of zero strength flows, with load instructions as the source of the flows, are predictable with very high accuracy using local prediction techniques, and that they account for around 3.08% of the totally dynamically executed instructions. We also observe that the prediction accuracies of the source and target of the same zero strength flow are not generally correlated. Holding a highly predictable target instruction from execution since it is connected via zero strength flow with a non-predictable load instruction can negatively impact the execution performance. We can attribute the results we obtained to the following:

- The results are related to zero strength flows, i.e. flows that have zero strength using all the three schemes used.
- Neither linear nor non-linear association exists between the source and target values.
- Highly predictable target instructions have strong self linear flow, which results in being highly predictable using local prediction techniques.

Data dependence occurs when an instruction reads a register or a memory location whose values depend on the execution of a previous instruction. Data dependence presents a limiting factor on ILP. We show that the existence of data dependence from a source to a target instruction is not a sufficient condition for the flow of information from the source to the target. Further work is required to check the possibility of exploiting paths that have zero flow strength to increase the effectiveness of ILP. Such paths are dependences where the source variables do not matter in the computation of the target variables values, thus making them irrelevant dependences to the execution.

VIII. Applications

In this section we describe the application of DITTANY in data value and indirect branch predictions.
We use DITTANY to identify the last instruction that updates the source operand of an indirect branch. We call this instruction the source instruction of the indirect branch. For an indirect branch instruction that is not highly predictable using the regular BTB technique [28], we predict its target address by accessing the prediction table using a value obtained by hashing the instruction pointer of the predicted indirect branch instruction with the outcome of its source instruction. We refer to this technique as BTBSrc. Our hybrid (BTB, BTBSrc) predictor is a combined predictor that remembers which of the predictors has made the best predictions in the past.

a) Benchmarks Characteristics: Table I presents the characteristics of indirect branch instructions in SPEC CPU 2006 benchmarks. We report the number of static instructions and static indirect branch instructions as well as the percentage of static indirect branch instructions with respect to the total number of static instructions. In addition, we present the percentage of dynamic indirect branch instructions with respect to the total number of dynamically executed instructions. We notice that indirect branch instructions account for 0.16% and 0.089% of the total static and dynamic instructions respectively.

b) Prediction Accuracy: Table II presents the prediction accuracy of indirect branch instructions using BTB and hybrid (BTB, BTBSrc). We use 16K tables for both BTB and BTBSrc. BTB prediction accuracy is 84.28%, while the hybrid (BTB, BTBSrc) achieves 95.46% prediction accuracy on average. BTBSrc alone with unlimited table size achieves 100% accuracy.

B. Application to Data Value Prediction

Using DITTANY, we select all instructions that have flows into them characterized by $|r| = 1$. We categorize the flows as follows: (i) flow from the instruction to itself, or (ii) flow from a source instruction into a target instruction. We define self linear relation type as the set of instructions that satisfy criterion (i) with strength of flow measured using standard $r$ equals to 1, and distinct linear relation type as the set of instructions that satisfy criterion (ii) and $|r| = 1$.

Using DITTANY, instructions are classified as either constant outcome instructions, or variable outcome instructions. Constant outcome instruction is an instruction that always produces the same value. Constant outcome instructions can be predicted with high accuracy using local last value predictor. For variable outcome instructions, we select instructions that exhibit (i) linear flow from the instruction to itself, and (ii) linear flow from a source instruction into the instruction of interest. For the instructions that satisfy criteria (i), we employ several local prediction techniques. For the instructions that satisfy criteria (ii), we predict the value $y$ of the instruction of interest, knowing the value $x$ of the source instruction using the linear equation $y = ax + b$. We use this technique when the instruction of interest neither follow a linear nor a FCM
TABLE I. CHARACTERISTICS OF SPEC CPU 2006 EVALUATED BENCHMARKS.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>astar</td>
<td>12224</td>
<td>26</td>
<td>2.13 x 10^-1</td>
<td>7.32 x 10^-4</td>
<td>2.23 x 10^4</td>
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<tr>
<td>gcc</td>
<td>848132</td>
<td>571</td>
<td>6.73 x 10^-2</td>
<td>2.8 x 10^-3</td>
<td>2.3 x 10^5</td>
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<tr>
<td>gobmk</td>
<td>234509</td>
<td>66</td>
<td>1.04 x 10^-1</td>
<td>4.1 x 10^-3</td>
<td>4.1 x 10^4</td>
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<tr>
<td>hmmer</td>
<td>89925</td>
<td>93</td>
<td>3.55 x 10^-2</td>
<td>6.8 x 10^-3</td>
<td>6.8 x 10^4</td>
</tr>
<tr>
<td>h264ref</td>
<td>166161</td>
<td>59</td>
<td>2.93 x 10^-1</td>
<td>7.22 x 10^-3</td>
<td>7.22 x 10^4</td>
</tr>
<tr>
<td>libquantum</td>
<td>10215</td>
<td>30</td>
<td>6.5 x 10^-1</td>
<td>1.9 x 10^-3</td>
<td>1.9 x 10^4</td>
</tr>
<tr>
<td>mcf</td>
<td>3389</td>
<td>22</td>
<td>8 x 10^-1</td>
<td>2.86 x 10^-4</td>
<td>2.86 x 10^4</td>
</tr>
<tr>
<td>omnetpp</td>
<td>152468</td>
<td>122</td>
<td>6.7 x 10^-2</td>
<td>9.45 x 10^-2</td>
<td>9.45 x 10^4</td>
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<td>perlbench</td>
<td>298936</td>
<td>200</td>
<td>1.78 x 10^-1</td>
<td>6.4 x 10^-2</td>
<td>6.4 x 10^4</td>
</tr>
<tr>
<td>sjeng</td>
<td>32012</td>
<td>57</td>
<td>2.46 x 10^-2</td>
<td>2.05 x 10^-1</td>
<td>2.05 x 10^4</td>
</tr>
<tr>
<td>xalancbmk</td>
<td>962864</td>
<td>237</td>
<td></td>
<td></td>
<td>2.31 x 10^-2</td>
</tr>
</tbody>
</table>

TABLE II. PREDICTION ACCURACY USING BTB AND HYBRID (BTB, BTBSrc).

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>BTB</th>
<th>Hybrid(BTB, BTBSrc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>astar</td>
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<tr>
<td>gcc</td>
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<tr>
<td>gobmk</td>
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<td>libquantum</td>
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<td>omnetpp</td>
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<td>sjeng</td>
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<tr>
<td>xalancbmk</td>
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<tr>
<td>SPEC CPU 2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Self linear relation type instructions measurements.

Figure 9. Constant outcome instructions measurements.

Figure 10. Distinct linear relation type instructions measurements.

Figure 9 shows that the last value predictor (LV) achieves on average 100% and 84.84% prediction accuracy and prediction coverage respectively for the selected constant outcomes instructions. These instructions account for 7.9% on average of the totally dynamically executed value producing instructions. Loads constitute 72.46% on average of these instructions.

Figure 8 shows that the instructions of the self linear relation type are highly predictable using local value prediction techniques. The local linear, 2-δ stride and DFCM predictors achieve on average 100%, 99.2%, and 90.56% prediction accuracy, and 90.81%, 96.7% and 73.6% prediction coverage respectively. Loads constitute 52.37% on average of these instructions.

Figure 10 shows that the global linear predictor achieves 98.98% prediction accuracy and 89.47% prediction coverage on average for instructions of the distinct linear relation type. It significantly outperforms all local predictors for this set.
of instructions. Instructions of this category present 6.1% on average of the totally dynamically executed value producing instructions. Loads constitute 88% on average of these instructions.

We have previously employed DITTANY in our work on value prediction [18].

IX. FUTURE WORK

Modern processors employ branch prediction and speculative executions to improve their performance, which have been shown to be prone to transient execution attacks [8]. In future work, we plan to use DITTANY to introduce new countermeasures using the information collected by the tool to prevent miss-training of prediction tables, and to introduce safe prediction techniques that are robust against existing side channels attacks. We will introduce approximate prediction techniques by leveraging our strength-based approach to quantify information flow in a non-binary manner. In addition, we will port DITTANY to DynamoRIO [7] since it supports IA-32, AMD64, ARM, and AArch64. Furthermore, we will implement dynamic information flow analysis in hardware, so that we can integrate our proposed techniques in real designs.

X. CONCLUSION

We described a Pin-based dynamic information flow analysis tool that identifies dynamic dependences in a binary executable and records the associated values induced at their sources and targets. We also computed the strengths of the identified dependences using information theoretic and statistical metrics applied on their associated values. We showed that the existence of data dependence from a source to a target instruction is not a sufficient condition for the flow of information from the source to the target. We presented and evaluated the usage of the proposed tool in data value and indirect branch predictions using SPEC CPU 2006 integer benchmarks.

Availability. The tool is publicly available with a detailed user guide under GNU GPLv3 at DITTANY repository.

ACKNOWLEDGMENTS

This work benefited from the support of the project ANR-19-CE39-0008 ARCHI-SEC.

REFERENCES


**APPENDIX**

A. SPEC CPU 2006 Benchmarks

Table III describes the SPEC CPU integer benchmarks we use.
<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Application Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>aat</td>
<td>Path-finding Algorithms</td>
<td>Pathfinding library for 2D maps, including the well known A* algorithm.</td>
</tr>
<tr>
<td>bzip2</td>
<td>Compression</td>
<td>Julian Seward’s bzip2 version 1.0.3, modified to do most work in memory, rather than doing I/O.</td>
</tr>
<tr>
<td>gcc</td>
<td>Compiler</td>
<td>Based on gcc Version 3.2, generates code for Opteron.</td>
</tr>
<tr>
<td>gobmk</td>
<td>Artificial Intelligence: Go</td>
<td>Plays the game of Go, a simply described but deeply complex game.</td>
</tr>
<tr>
<td>hmmer</td>
<td>Search Gene Sequence</td>
<td>Protein sequence analysis using profile hidden Markov models (profile HMMs).</td>
</tr>
<tr>
<td>h264ref</td>
<td>Video Compression</td>
<td>A reference implementation of H.264AVC, encodes a videotream using 2 parameter sets. The H.264AVC standard is expected to replace MPEG2.</td>
</tr>
<tr>
<td>libquantum</td>
<td>Physics, Quantum Computing</td>
<td>Simulates a quantum computer, running Shor’s polynomial-time factorization algorithm.</td>
</tr>
<tr>
<td>mcf</td>
<td>Combinatorial Optimization</td>
<td>Vehicle scheduling. Uses a network simplex algorithm (which is also used in commercial products) to schedule public transport.</td>
</tr>
<tr>
<td>omnetpp</td>
<td>Discrete Event Simulation</td>
<td>Uses the OMNet++ discrete event simulator to model a large Ethernet campus network.</td>
</tr>
<tr>
<td>perlbench</td>
<td>Programming Language</td>
<td>The workload includes SpamAssassin, MHonArc (an email indexer), and specdiff (SPEC’s tool that checks benchmark outputs).</td>
</tr>
<tr>
<td>sjeng</td>
<td>Artificial Intelligence: chess</td>
<td>A highly-ranked chess program that also plays several chess variants.</td>
</tr>
<tr>
<td>xalancbmk</td>
<td>XML Processing</td>
<td>A modified version of Xalan-C++, which transforms XML documents to other document types.</td>
</tr>
</tbody>
</table>