Packet Processing Algorithm Identification using Program Embeddings

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
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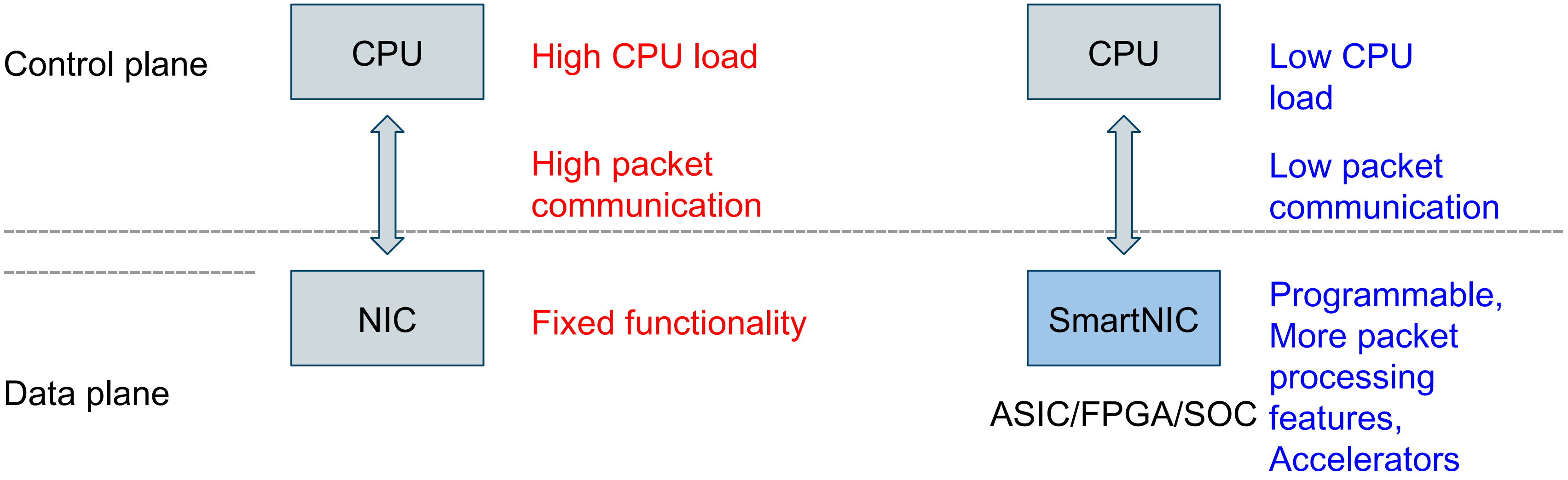
Introduction: Overall theme

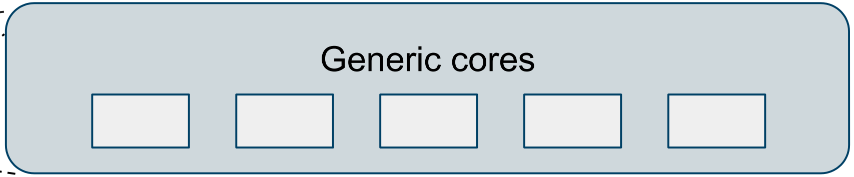
Fact: CPU packet-processing speeds ⋘ network speeds

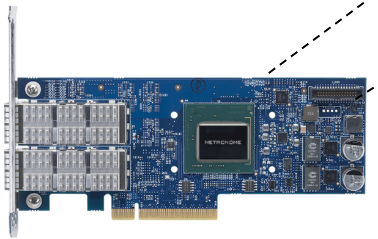
SmartNICs: High speed programmable hardware for packet processing



SmartNICs

- Generic cores for packet processing specified by Network Function (NF) program





Significant performance improvements

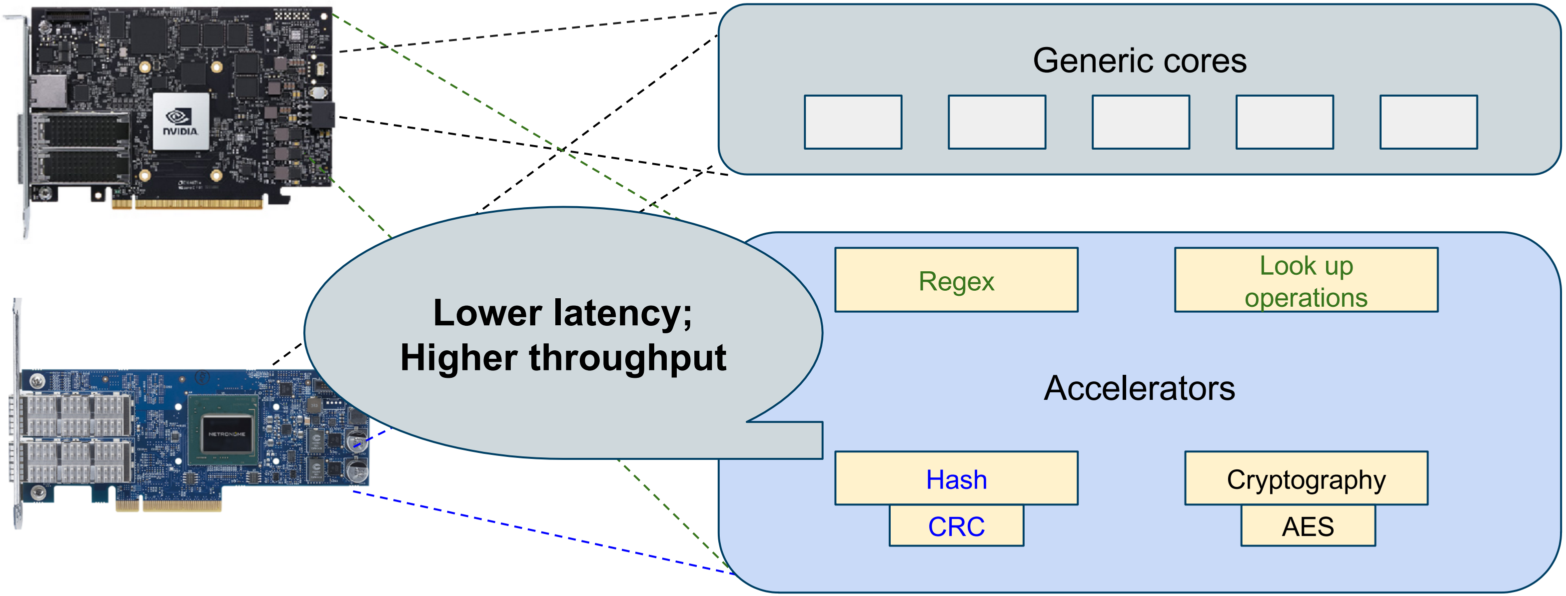
- Latency, throughput and power

IPipe[1]: IPSec program achieved 22.9 Gbps on 25GbE SmartNIC

IPIPE[1]: Offloading Distributed Applications onto SmartNICs Using IPipe: Ming Liu, Tianyi Cui, Henry Schuh, Arvind Krishnamurthy, Simon Peter, and Karan Gupta (ACM Special Interest Group on Data Communication 2019)

SmartNICs

- Hardwired logic for frequently used operations and algorithms

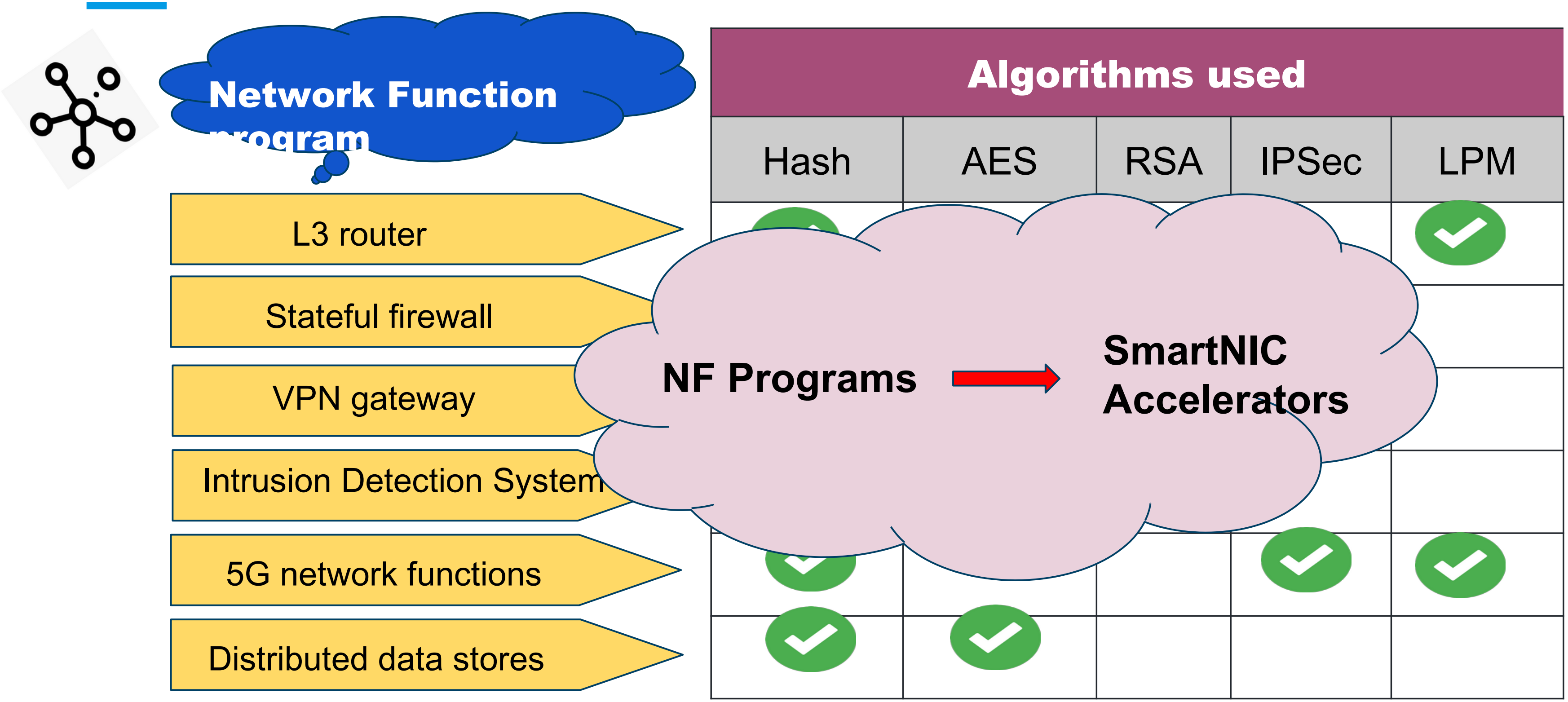


Goal: Offloading NF programs from CPUs to SmartNIC accelerators

Accelerators available on SmartNICs

SmartNIC model	Algorithms with Accelerator Support				
	Hash	AES	RSA	IPSec	LPM
Netronome Agilio CX	✓	✓	✓	✓	✓
Nvidia Bluefield 3 DPU		✓	✓	✓	
Cavium LiquidIO				✓	
Marvell OCTEON 10		✓		✓	
Pensando DSC-100	✓	✓		✓	✓
⋮					

Network Functions and Associated Algorithms



Difficulties in Mapping

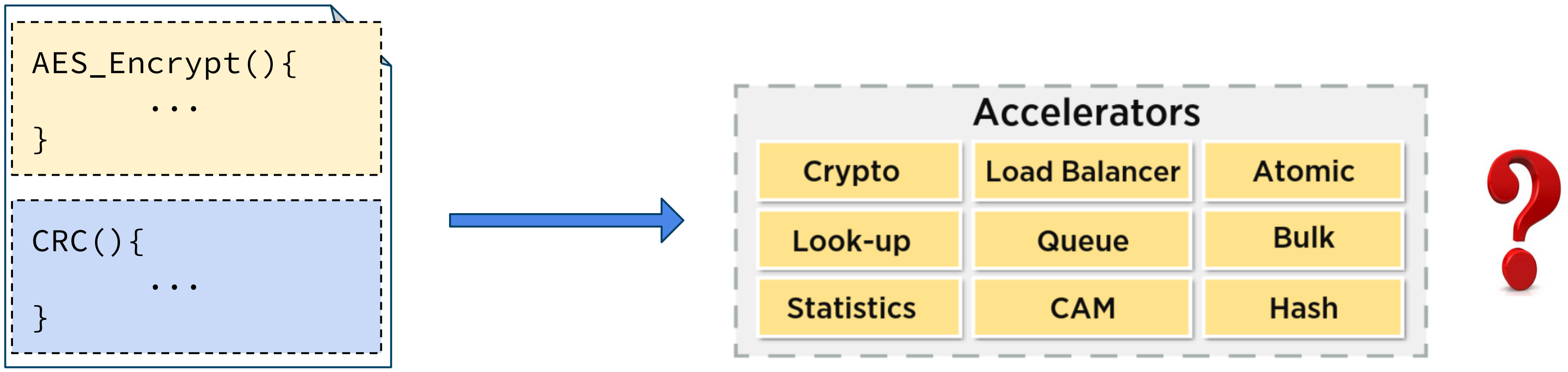
- Identification of regions of code suitable for accelerators
  - Same algorithm can be implemented in multiple ways
- Porting to SmartNICs needs analysis and multiple rounds of manual tuning
  - Tune program by utilizing SmartNIC accelerators

Identifying + Mapping NF to SmartNIC is a tedious and laborious process

Can this process be simplified?

Problem Statement

- Need a workflow to simplify the cross-platform porting process
- Automatic identification of regions in Network Functions



Network Function

Accelerators Figure Source: Netronome NFP-4000 Flow Processor Product Brief

Approach

Our view: This is a ML classification problem.

Our approach:

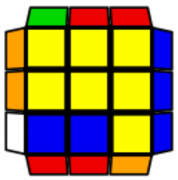
- **Use Compilers** to aid developers to map NF program to SmartNI 
- **Use ML** to identify code regions performing a specific task (algorithm) 
- **Create realistic dataset** of packet processing algorith 

Why ML?

- **Undecidability**
  - It is hard to identify algorithms in a program

- **Laborious**
  - Manually assigning accelerators for functions in a large NF program is tedious

- **Scale of variation**
  - Diverse algorithms and SmartNIC architectures



Challenges

1. **Represent** algorithms and programs as input to ML model

2. **Create dataset** of packet processing algorithms
   - Realistic
   - Diverse
   - Wide range of applicability

Challenge #1: Representations of Programs

Background: LLVM IR

LLVM IR: LLVM IR is the Intermediate Representation (IR) of the LLVM compiler toolchain.

C → Front-end → **LLVM IR**

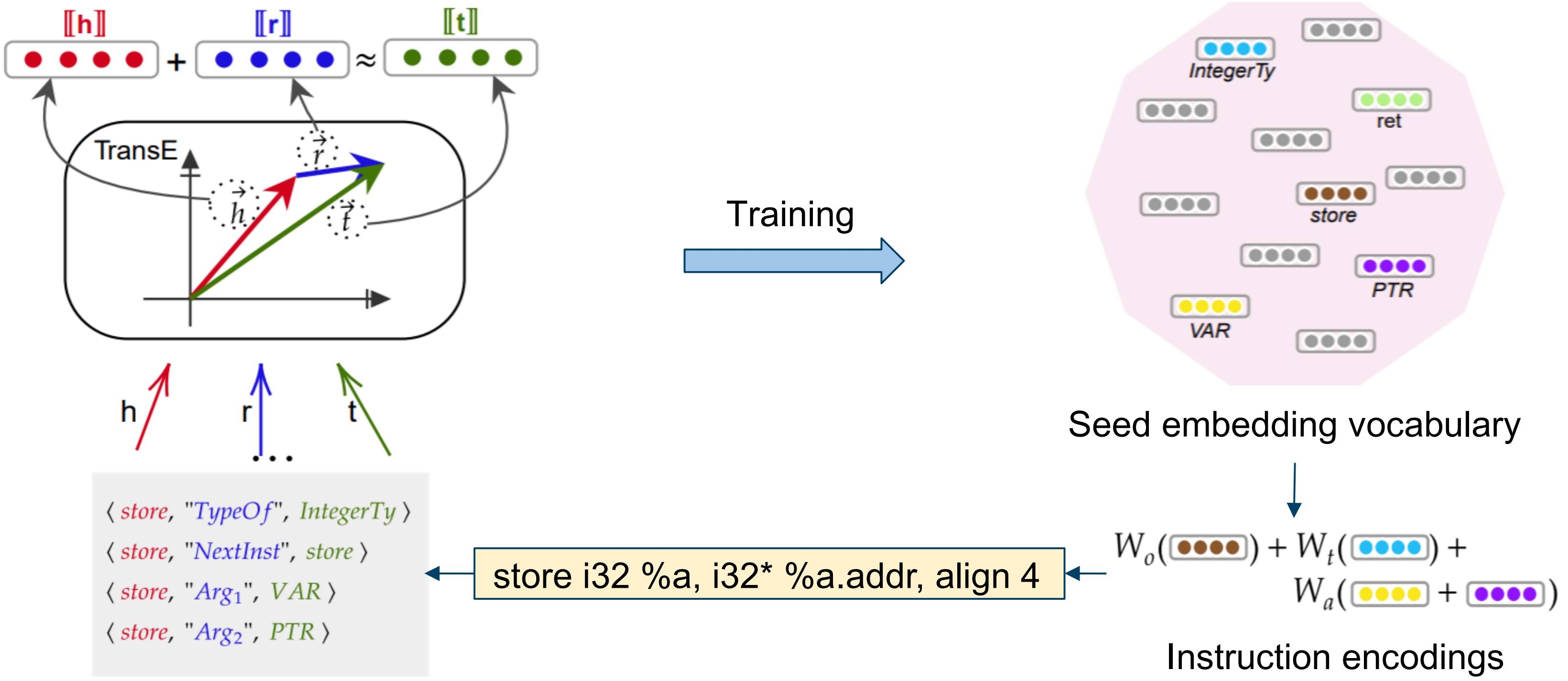
```c
int sum(int a, int b)
{
    return (a+b);
}
```

```llvm
define i32 @sum(i32 %a, i32 %b) #0 {
entry:
 %a.addr = alloca i32, align 4
 %b.addr = alloca i32, align 4
 store i32 %a, i32* %a.addr, align 4
 store i32 %b, i32* %b.addr, align 4
 %0 = load i32, i32* %a.addr, align 4
 %1 = load i32, i32* %b.addr, align 4
 %add = add nsw i32 %0, %1
 ret i32 %add
}
```

Background: Program Representations

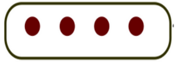
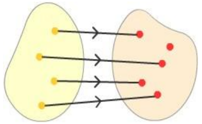
Various techniques in use	Information captured
Collecting **features** using domain expertise	Specific task (Domain expertise)
Programs as **tokens** of natural languages	Syntactic
Abstract Syntax Tree representations	Syntactic + Limited Semantic
IR-based representations	Syntactic + Semantic + Generalized

Background: IR2Vec: IR based Program Embeddings

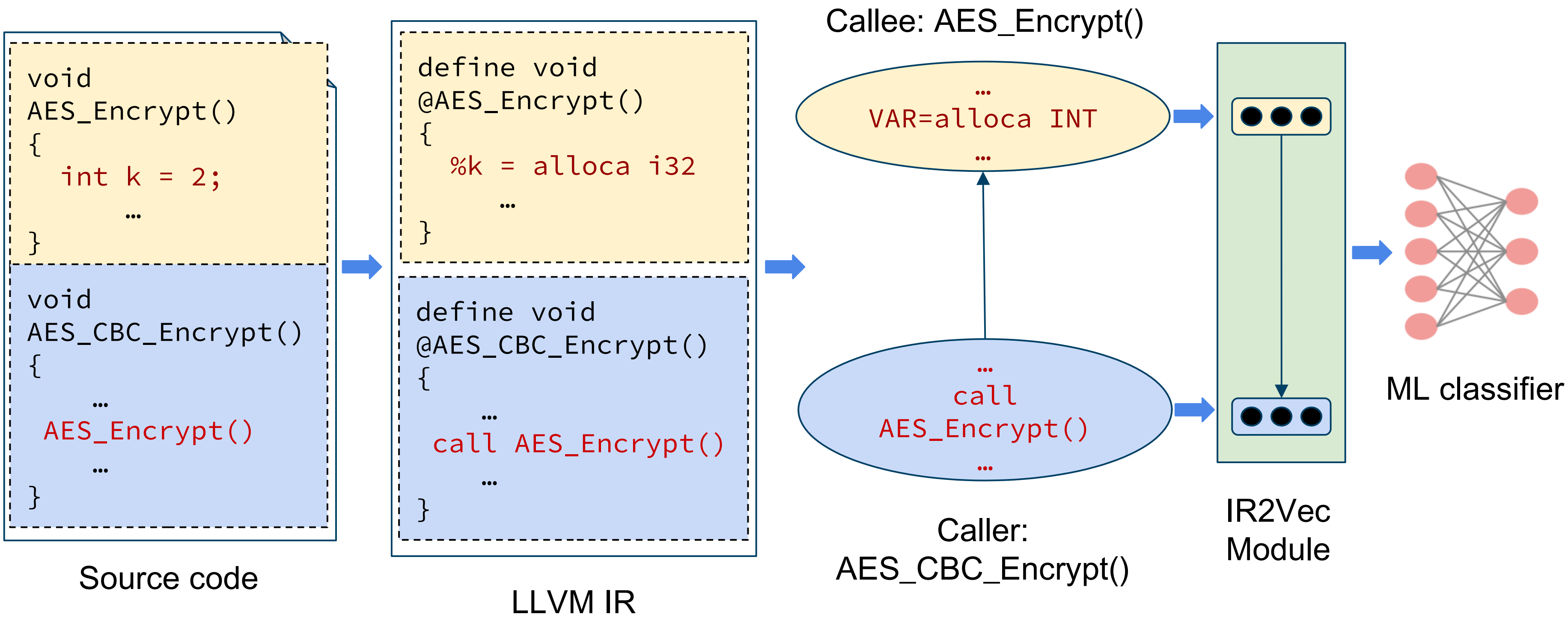


IR2Vec: LLVM IR based Scalable Program Embeddings: S. VentakaKeerthy, Rohit Aggarwal, Shalini Jain, Maunendra Sankar Desarkar, Ramakrishna Upadrasta, Y. N. Srikant (ACM Transactions on Architecture and Code Optimization 2020)

Proposed Methodology

- Identify appropriate accelerators for the program 
  - Use ML based techniques
- Utilize IR2Vec embeddings 
  - Encodes syntactic and semantic information of the program
- Predict accelerator label for each function 

Proposed Methodology (contd.)



Challenge #2: Generation of Dataset

Dataset Creation

- ML needs more data
  - ImageNet - 14 million images
  - COCO - 330K images
- Lack of availability of sufficient real world NF programs
  - Earlier datasets [Clara]: only around 7.5k programs

- Need to create a custom dataset
  - using programs from NF domain

Clara: Automated SmartNIC Offloading Insights for Network Functions: Yiming Qiu, Jiarong Xing, Kuo-Feng Hsu, Qiao Kang, Ming Liu, Srinivas Narayana, Ang Chen (ACM Symposium on Operating Systems Principles 2021)

Initial Steps: Seed Dataset Collection

Seed dataset: Collected functions for algorithms used in cryptography libraries

Library / Algorithm	OpenSSL (v1.1)	OpenSSL (v3)	CryptoPP (v8.6)	Botan (v2.19)	Nettle (v3.7)	WolfCrypt (v5.1)	MbedTLS (v3.1)	**Total**
AES	8	7	8	6	2	6	5	**42**
DES	13	13	8	4	4	2	4	**48**
RSA	5	7	4	5	0	7	3	**31**
Total	**26**	**27**	**20**	**15**	**6**	**15**	**12**	**121**

Dataset Expansion using Compiler Transformations

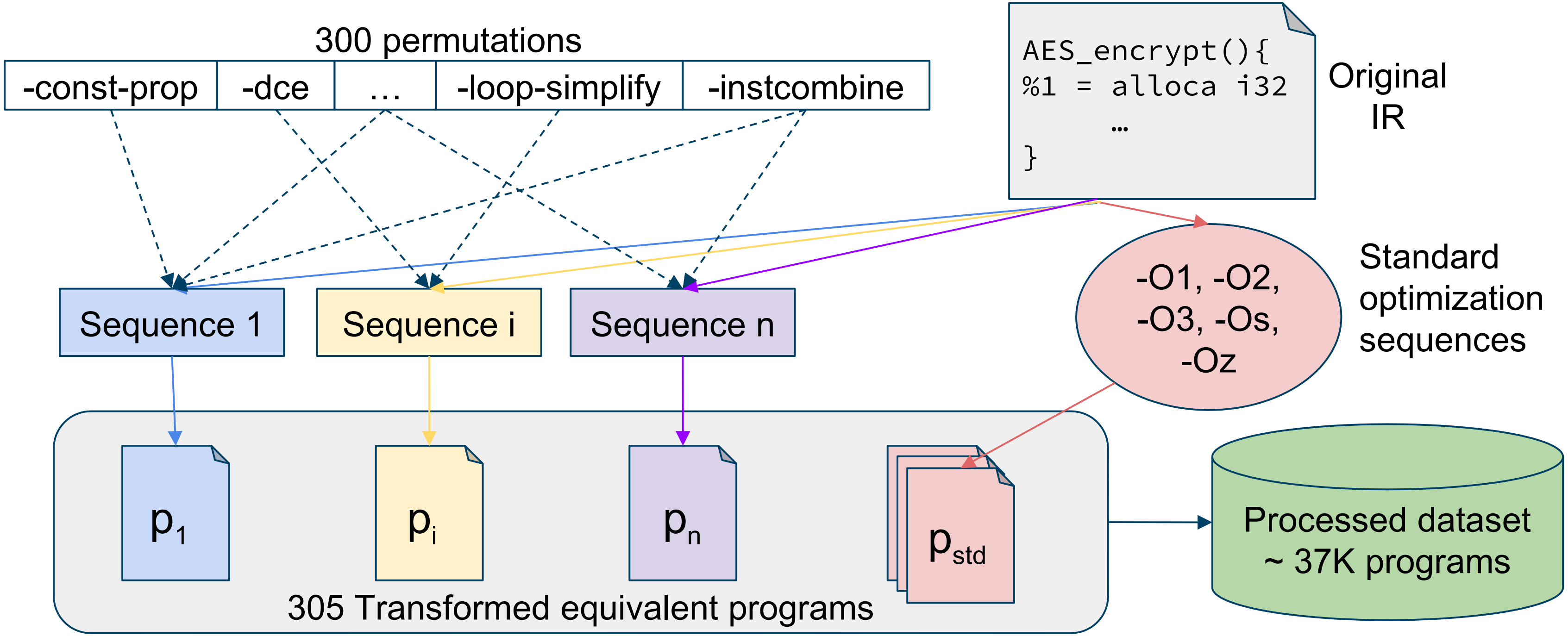
Method: Apply compiler transformations on original (seed) NF programs

- Adds diversity to dataset
  - Code size of the program
  - Latency
  - Throughput
  - Power usage
- Semantics of original codes are preserved

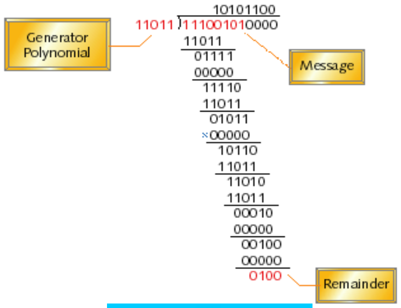
Result: Produces sufficient data for training a ML model

Dataset Expansion using Compiler Transformations

- Apply random permutations of LLVM transformations to programs



Experimentation & Implementation details



Experimentation

- **Detection of CRC algorithm**
  - Classifying CRC and non-CRC programs
- **Detection of cryptography algorithms**
  - CRC, AES, DES/3DES, RSA, non-NF programs

Implementation

- Manually labelled functions for classification
- Used IR2Vec embeddings of programs compiled to LLVM IR (v12.0)
- Compared results from our approach with Clara

Clara: Automated SmartNIC Offloading Insights for Network Functions: Yiming Qiu, Jiarong Xing, Kuo-Feng Hsu, Qiao Kang, Ming Liu, Srinivas Narayana, Ang Chen (ACM Symposium on Operating Systems Principles 2021)

Results: Precision

Model	CRC		CRC + Cryptography	
	Clara	IR2Vec	Clara	IR2Vec
Gradient Boosted Decision Tree	0.992	0.974	0.664	0.949
Decision Tree	0.983	0.994	0.661	0.969
Multi-layer Perceptron	0.983	0.997	0.666	0.959
Support Vector Machine	0.992	0.999	0.646	0.898
k-Nearest Neighbour	0.980	0.999	0.596	0.976
AutoML	0.980	0.999	0.661	0.979

Results: Recall

Model	CRC		CRC + Cryptography	
	Clara	IR2Vec	Clara	IR2Vec
Gradient Boosted Decision Tree	0.435	0.997	0.594	0.947
Decision Tree	0.488	0.995	0.622	0.968
Multi-layer Perceptron	0.437	0.999	0.590	0.958
Support Vector Machine	0.484	0.995	0.604	0.894
k-Nearest Neighbour	0.486	0.999	0.630	0.974
AutoML	0.487	0.999	0.621	0.978

Results: F1 Score

Model	CRC		CRC + Cryptography	
	Clara	IR2Vec	Clara	IR2Vec
Gradient Boosted Decision Tree	0.605	0.985	0.627	0.948
Decision Tree	0.652	0.994	0.641	0.968
Multi-layer Perceptron	0.605	0.998	0.626	0.958
Support Vector Machine	0.651	0.997	0.624	0.896
k-Nearest Neighbour	0.650	0.999	0.613	0.975
AutoML	0.651	0.999	0.640	0.978

IR2Vec can capture semantics of the algorithm

Summary & Future Work

Contributions

- Using embedding techniques (IR2Vec) to represent programs from network domain
- Modeling algorithm identification problem with a scalable ML approach
- Realistic dataset collection and generation of semantically equivalent programs

Future Work

- Applying to real-world network functions
- Identifying other algorithms

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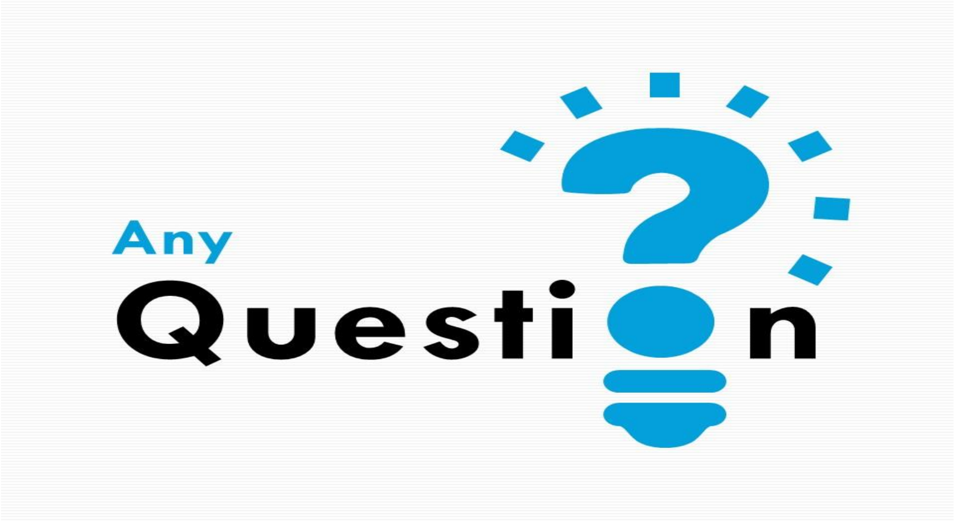
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