RAPID: Accelerating Pattern Search Applications with Reconfigurable Hardware

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Finding Needles in a Haystack

- Researchers and companies are collecting increasing amounts of data
- 44x data production in 2020 than in 2009†
- Demand for real-time analysis of collected data‡

† Computer Sciences Corporation. Big data universe beginning to explode. 2012
‡ Capgemini. Big & fast data: The rise of insight- driven business. 2015.

What is the common theme?

Locate the most probable location for a DNA fragment in the human genome

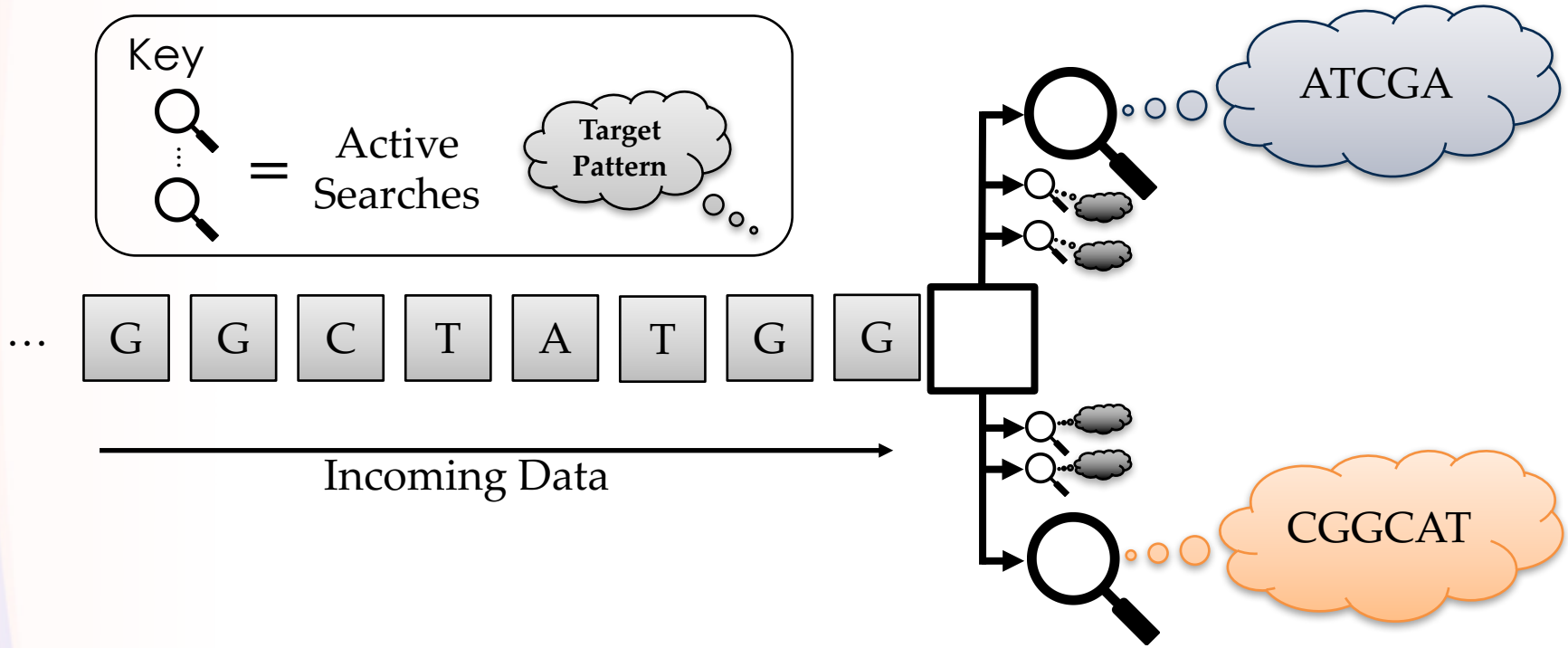
Identify consumer sentiment based off of social media posts

Find products that are most commonly purchased together

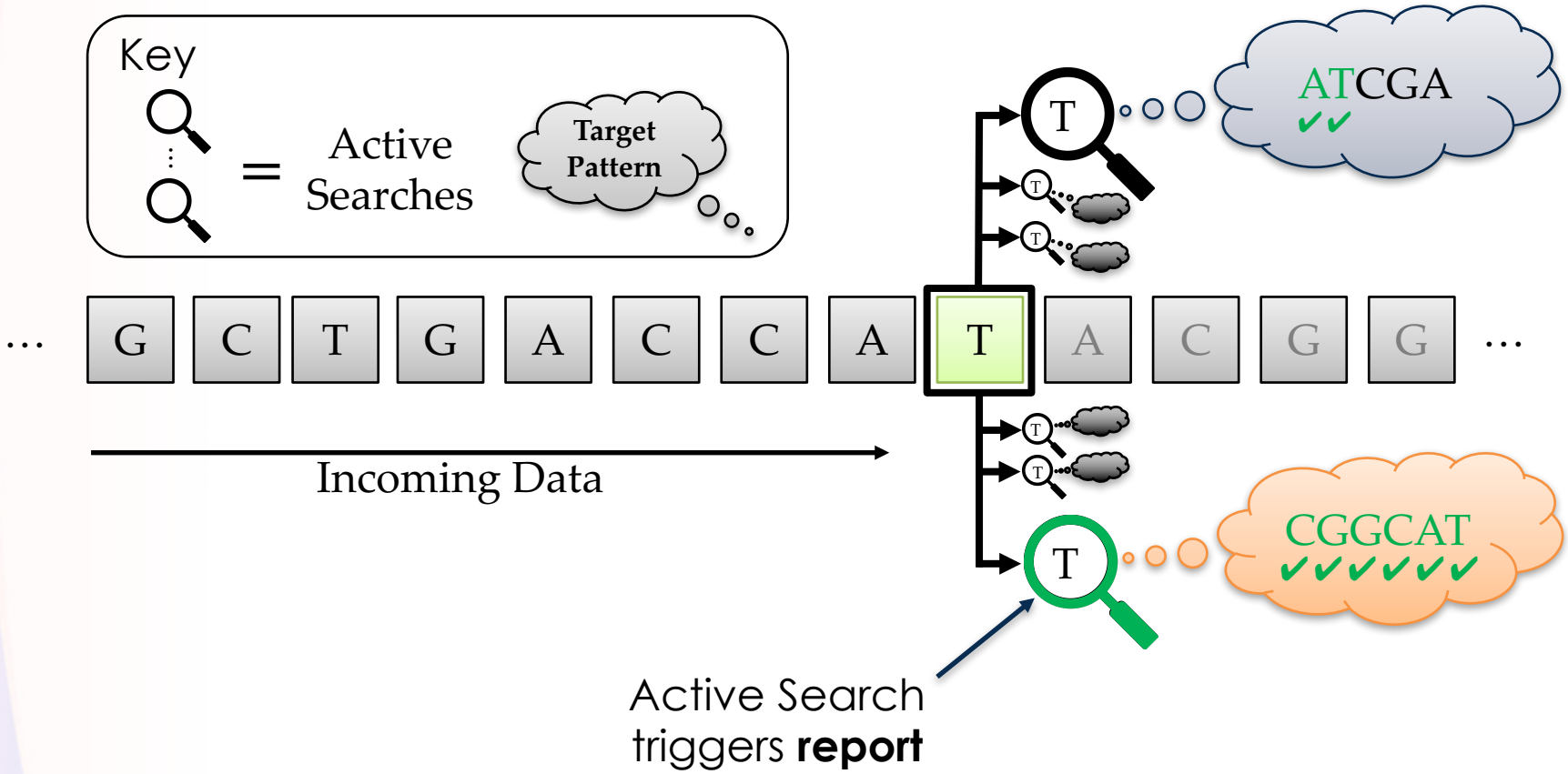
Search for Higgs events based off on paths of subatomic particles

Pattern Search Problems

Parallel searches



Parallel searches



Parallel Searches: Goals

- Fast processing

Specialized Hardware
+ VASim

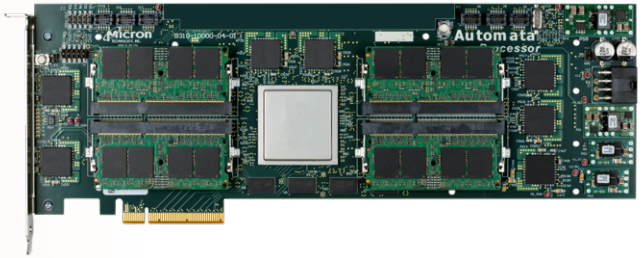
- Concise, maintainable representation
- Efficient compilation
  - High throughput
  - Low compilation time

RAPID
Programming
Language

Specialized Hardware

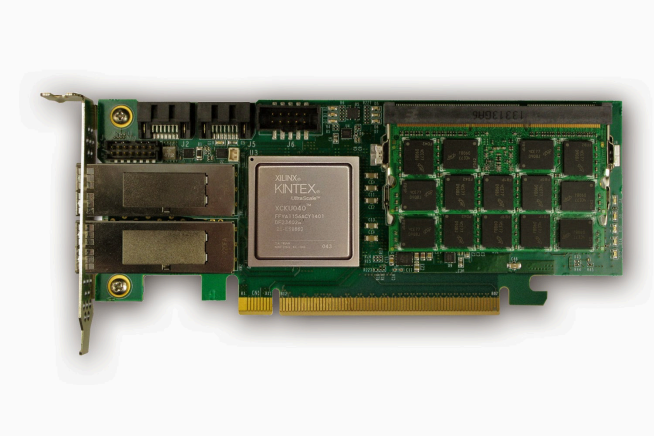
Micron Automata Processor

- Memory-derived hardware implementation of non-deterministic finite automata
- Accelerates identification of patterns in input data stream using massive parallelism



FPGAs

- Logic-based reconfigurable fabric of LUTs and Memory
- Allow custom implementation of applications for high-speed processing



A researcher should spend his or her time designing an algorithm to find the important data, not building a machine that will obey said algorithm.

The Remainder of this Talk

- Automata Processing
  - Current Programming Models
- RAPID Programming Language
  - Language Overview
- VASim: Virtual Automata Simulator
  - Synthesizable Verilog Generation
- Experimental Evaluation
- Conclusions and Future Directions

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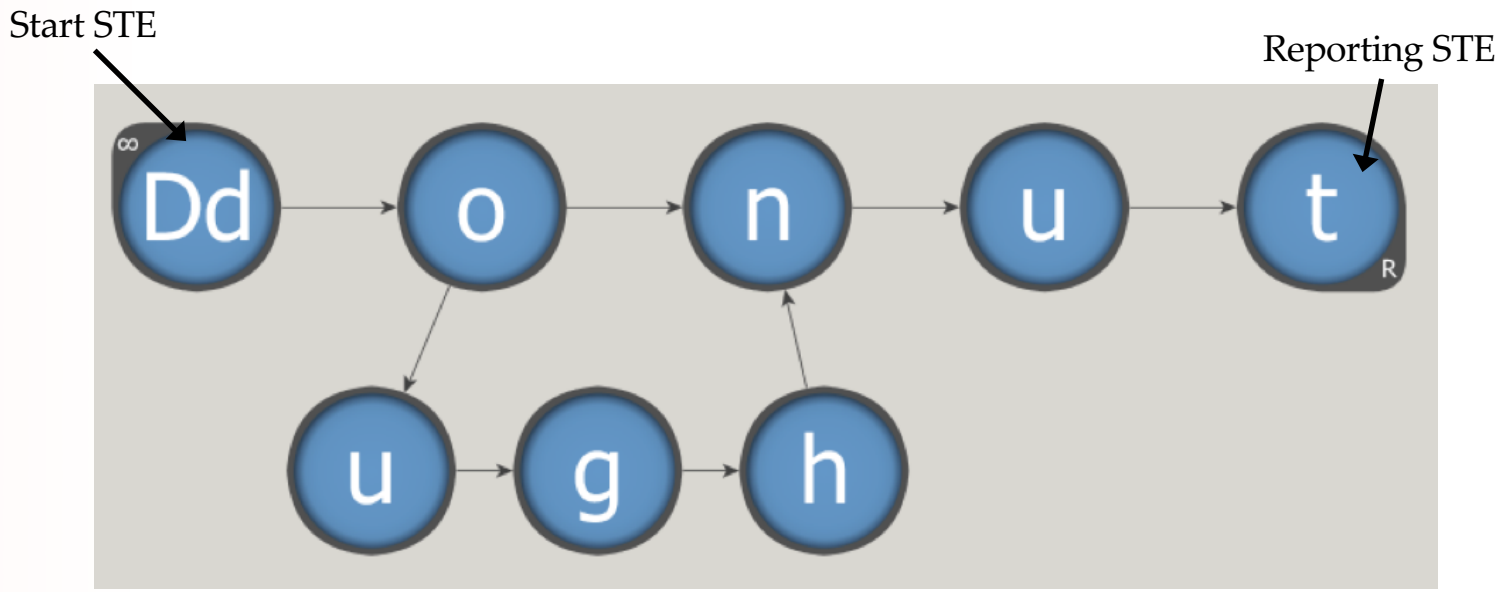
Finite Automata

- Useful for filtering data based on patterns
- Equivalent in representative power to Regular Expressions



.*[Dd](o|ough)nut

Programming Challenges

- Finite automata development akin to **assembly programming**
  - Requires knowledge of automata theory **and** hardware properties
  - Tedious and error-prone development process
  - In many areas, specification of FA is automated!
- Regular expressions challenging to implement
  - Often exhaustive enumerations
  - Similarly error-prone (high rates of runtime exceptions)

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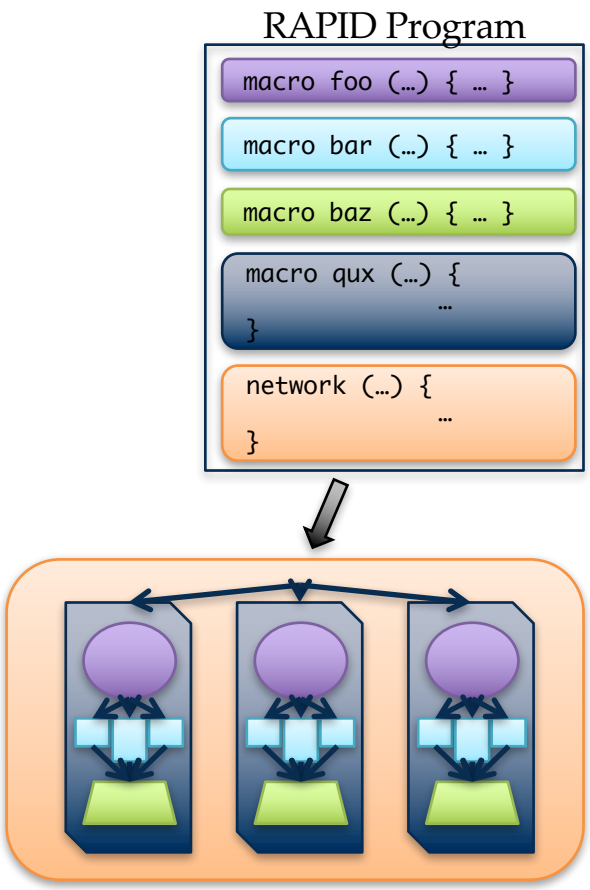
RAPID at a Glance

- Provides concise, clear, maintainable, and efficient representations for pattern-identification algorithms
- Conventional, C-style language
- Domain-specific parallel control structures
- Provides suitable data structures for pattern search problems
- Recursive algorithm to transform RAPID program in to finite automaton for execution



Example RAPID Program

Association Rule Mining
Identify items from a database that frequently occur together

Example RAPID Program

Spawn parallel computation for each item set

```
macro frequent (String set, Counter cnt) {
        foreach(char c : set) {
            while(input() != c);
        }
        cnt.count();
}

network (String[] set) {
    some(String s : set) {
        Counter cnt;
        whenever(START_OF_INPUT == input())
            frequent(s,cnt);
        if (cnt > 128)
            report;
    }
}
```

Example RAPID Program

Spawn parallel computation for each item set

Sliding window search calls *frequent* on every input

```
macro frequent (String set, Counter cnt) {
        foreach(char c : set) {
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Example RAPID Program

If all symbols in item set match, increment counter

Spawn parallel computation for each item set

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Example RAPID Program

If all symbols in item set match, increment counter

Spawn parallel computation for each item set

Sliding window search calls *frequent* on every input

Trigger *report* if threshold reached

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macro frequent (String set, Counter cnt) {
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```
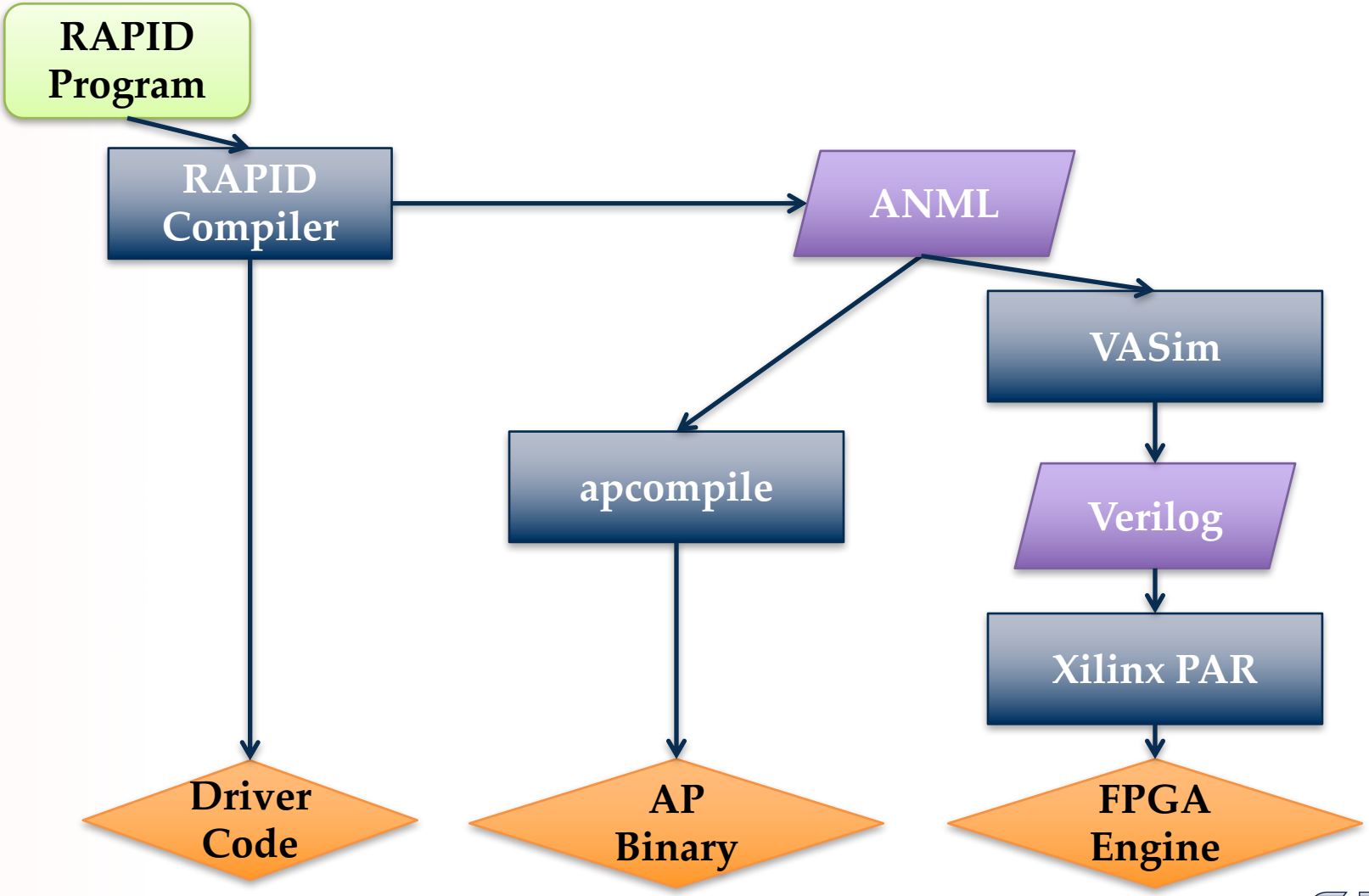

System Overview



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VASim: Open-Source Automata Processing Platform

- Standard platform for automata application and architecture research
- **Highly flexible**: Can be arbitrarily extended with hypothetical functionality
- **Common Algorithm Repository**: standard location for both old (DFA subset construction, prefix merging) and new (hybrid finite automata) automata optimizations
- **High-Performance**: on-par with industrial quality regex engines like RE2/HyperScan

Generating Verilog

- **Inputs**: clock, reset, 8-bit input symbol
- **Outputs**: report events

- Update activations every clock cycle
- State activations stored in registers
- Activate state if
  - State accepts input symbol
  - State with incident edge is active

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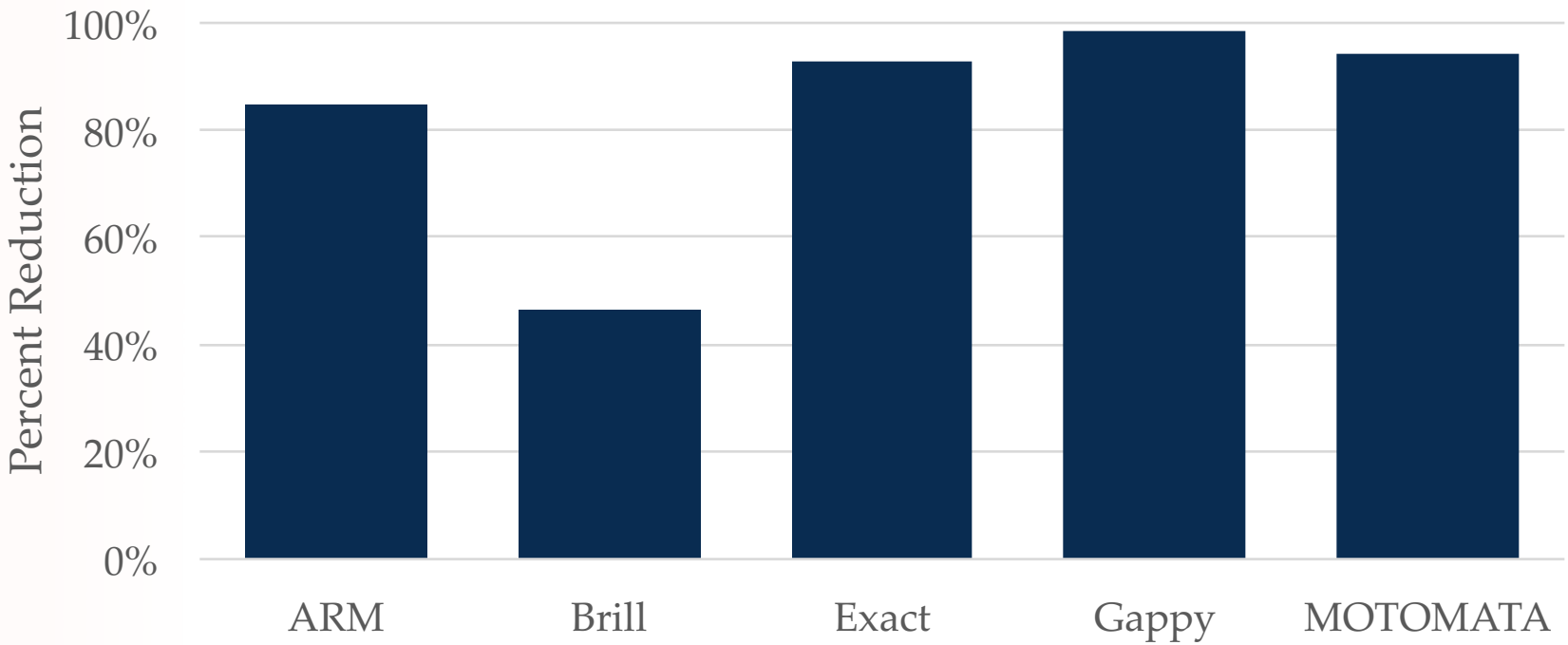
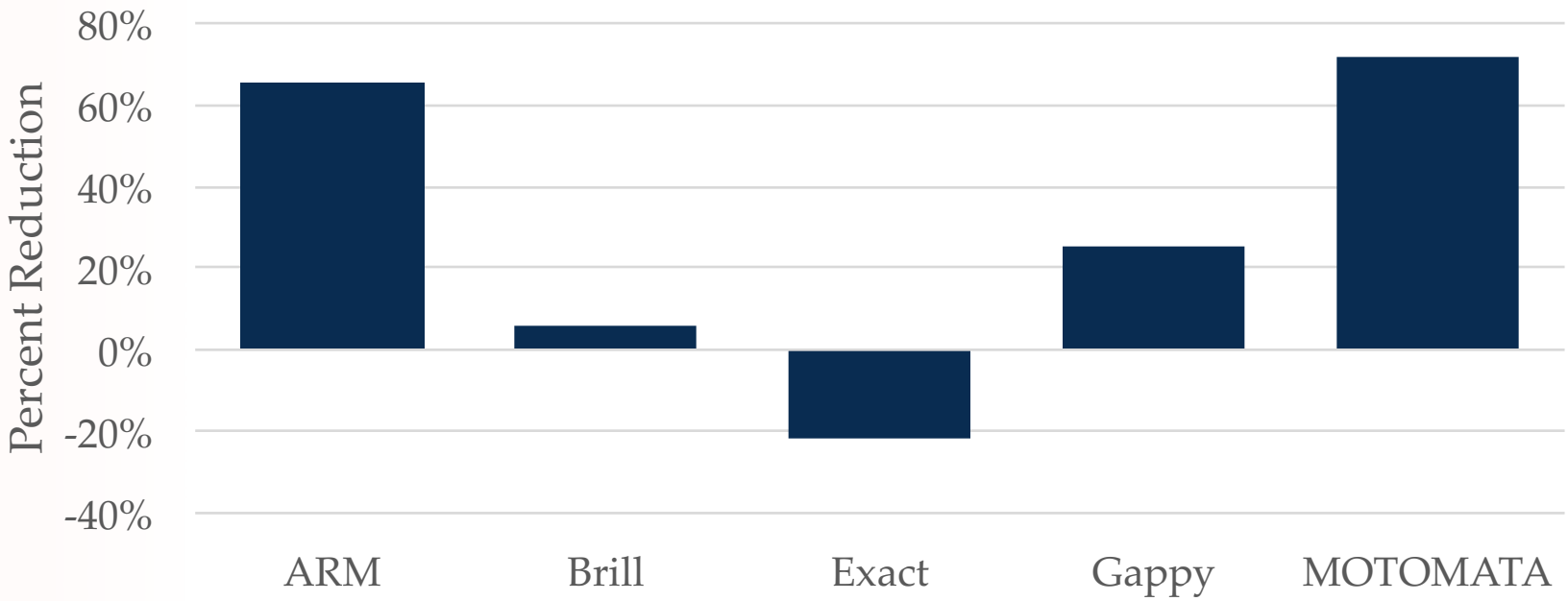
Description of Benchmarks

Benchmark	Description	Domain	Baseline Generation Method
ARM	Association Rule Mining	ML	Meta Program
Brill	Brill Part of Speech Tagging	NLP	Meta Program
Exact	Exact DNA Alignment	Bioinformatics	ANML
Gappy	DNA Alignment with Gaps	Bioinformatics	ANML
MOTOMATA	Planted Motif Search	Bioinformatics	ANML

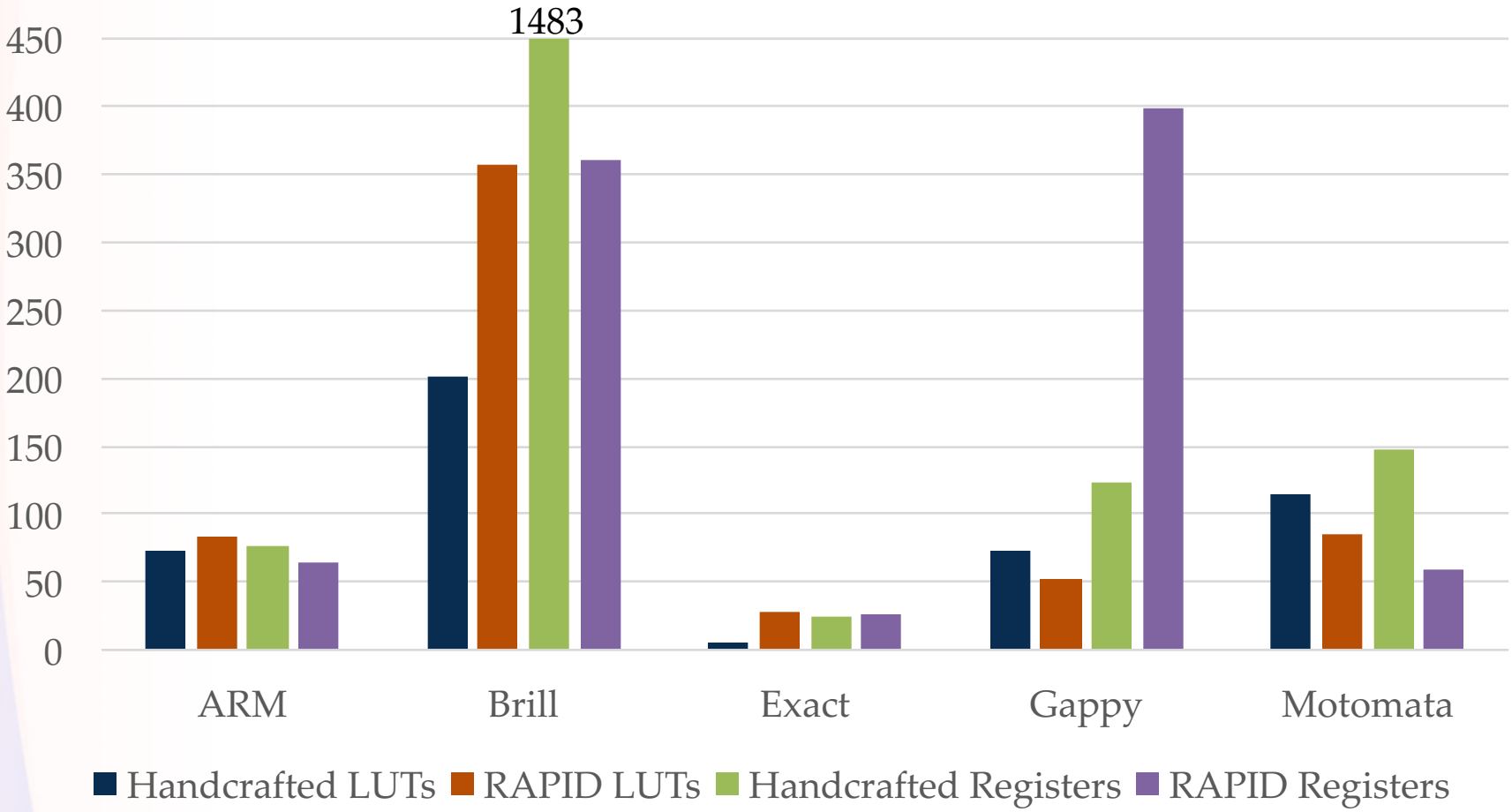
RAPID Lines of Code



Generated STEs (Automata Processor)



Generated LUTs and Registers (FPGA)



Xilinx Kintex UltraScale XCKU060

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Hardware-Agnostic RAPID

- Does RAPID provide true hardware-agnostic representation of pattern search?
- Full timing evaluation on FPGA
  - Implementation of custom reporting architecture
- Evaluation with CPU and GPGPU engines

Tech Transfer

- Industry collaborators
  - Contacts with Micron and Xilinx
  - Center for Automata Processing brings together researchers and industry experts
- Publications/presentations
  - Associated work presented at ASPLOS 2016 and Supercomputing Frontiers 2016
  - Weekly/semiweekly teleconferences with Micron and Xilinx to present research
- Tools will be released open source (BSD)

Conclusions

- RAPID is a **concise**, **maintainable**, and **efficient** high-level language for pattern-search algorithms
- VASim is an **extensible** and **general** framework for automata application and architecture research
- Combination of these tools allows for efficient execution using the Automata Processor, FPGAs

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EXTRA SLIDES

Programming Challenges

- Implement **single instance** of a problem
  - Each instance of a problem requires a brand new design
  - Need for meta-programs to generate final design

- Current programming models place unnecessary burden on developer

Parallel searches