GPU-accelerated Keyword Matching and Expression Evaluation for Real-time Text Search

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Background

- Salesforce Marketing Cloud provides the following:
  - Social listening
  - Social content
  - Engagement
  - Workflow and automation
  - Social advertisements
  - Measurement

- Social listening is provided by our Radian6 technology, acquired in 2011
  - We target the entire social web for monitoring and engagement
Background

- **Keyword-matching**
  - Central to all of our listening capabilities
  - Forms the basis of all our search functionality

- **Use cases**
  - **Content acquisition**
    - Check all incoming content for relevancy
  - **Content search**
    - Search content in our database for items that match a particular topic profile
Background

- A keyword is a string of characters defining a discrete word or phrase that is to be matched
- Eg., “apple”, “orange”, “justin bieber”
- For a keyword to be matched, it must be bounded by whitespace (not a substring of a longer word/phrase)
- Keyword expressions are sets of keywords logically combined with Boolean operators
- Eg., “mango” AND (“horrible” OR “delicious”)


Scale of Content Acquisition

- **Documents**
  - Need to handle about 450M incoming tweets per day
    - And growing...
  - Also need to handle every other type of content we acquire

- **Keywords**
  - Over 1.6M search expressions defined in our topic profiles
    - This is growing quickly with our customer base
  - Expressions are becoming more expensive to evaluate
    - Each expression averages about 12 inclusive keywords
    - Customers are learning that more keywords can give better specificity for listening
Old Approach

- **Apache Lucene**
  - Java library which provides comprehensive indexing and search capabilities for Boolean keyword expressions
  - Easy to use and integrate into a tech stack

- **Twitter workers**
  - Build an index for a large batch of tweets, then query every expression against the index
  - Low throughput, high latency
What’s the problem?

- **Latency**
  - It takes roughly 5 minutes for a Twitter worker to process a batch of ~8k tweets against the full expression set
  - Sometimes can take up to 12 minutes
  - For Twitter content that is supposed to be real-time, some of our customers found this unacceptable

- **Throughput**
  - Roughly 80 multithreaded Twitter workers were needed to keep up with the Twitter Firehose of Public Tweets
  - Spikes on the Firehose caused backups in our queues, introducing more latency and requiring extra workers to remove the backlog
New Approach – Zapp

- Accelerated hardware
  - High-throughput GPUs
  - Run keyword-matching controller on CPU and push compute-intensive tasks to GPU

- Better algorithm
  - Search keywords simultaneously in parallel, then evaluate keywords against Boolean expressions
  - Prune the expression search space to reduce the number of expression evaluations
Zapp Engine

Zapp

- Main Loop Thread
- Text Server Thread
- Results Server Thread
- Expression Server Thread
- Log Server Thread
- Build Process
Algorithm Pseudo-code

preprocess expressions
while true:
  get document batch from text server
  for each document:
    find all keyword matches
  for each document:
    find all keyword expressions which evaluate as true
  push results to results server
First CUDA kernel
Second CUDA kernel
Keyword-matching Kernel

- Implements parallel Aho-Corasick
  - Goto, failure, and output functions are pre-computed on CPU
- Functions are serialized as a state transition table
- Documents enter as linear buffer with an index marking the document boundaries
- Text is divided into chunks of a fixed number of bytes
  - Each chunk maps to a CUDA thread
- Matches are stored as binary flags in a bitmap
Aho-Corasick

- Construct a goto function representing all unique keywords from all expressions
- Define failure and output functions for each node in the tree
- Step through a text stream, byte-by-byte, walking through the tree according to functions

Shelly had a husband. His name was Herbert, but she didn’t like his cooking and he found her bothersome.
Expression Evaluation Kernel

- Evaluate Boolean expressions against binary matching flags from the bitmap
- Each CUDA thread maps to one comparison (a unique pair of document and expression)
- Expressions can be nested
- Expressions are sorted by size and grouped into CUDA blocks for more efficient execution
- Possible to heavily optimize this process
Shelly had a husband. His name was Herbert, but she didn’t like his cooking and he found her bothersome.

“husband” AND “cooking” AND (“delicious” OR “like”)
“delicious” AND “cooking” AND (“husband” OR “wife”)

Keywords: he, she, his, hers
Improvement

- Keyword-matching happens very quickly, but expression evaluation is slow
  - Checking each expression against each document is effectively an exhaustive search, taking roughly 95% of the runtime
  - Will become increasingly expensive with increasing expressions

- Time to evaluate an individual expression is independent of document size or keywords matched

- If we can guarantee that all expressions are inclusive (no NOT operators), then we can prune the expressions search space
Expression Space Pruning

- Perform a Boolean OR reduction for all keyword matches across a batch of documents
- Evaluate the reduced keyword matches against all expressions
- Expressions which evaluate as true form the pruned expression set
  - May have false positives
  - Guaranteed no false negatives
- Perform fine-grained matching of each document in the document batch against each of the pruned expressions
  - Eliminates false positives
Expression Space Pruning

- Two stages
  - Coarse-grained pruning to remove the vast majority of expressions from the search space (for each document batch)
  - Fine-grained to eliminate false positives and decide exactly which expressions match which documents

- Performance depends on a number of characteristics
  - Most are data-dependent

- Can be generalized to a multi-stage approach for improved performance, but we use two for simplicity

- Let’s model the performance
Mathematical Model

\[ C_{total} = C_1 + C_2 \]

\[ C_1 = \frac{d \times e}{b} \]

\[ C_2 = d \times E(b) \]

\[ E(b) \] is the average number of expressions we would expect to match a document batch of size \( b \). This is determined empirically and is best modeled with a quadratic function.

- \( c \): comparisons
- \( e \): expressions
- \( d \): documents
- \( b \): batch size
- \( E(b) \): expected matches
Optimization

- We wish to minimize the number of expression evaluations (i.e., document-expression comparisons)
- Free variable: documents per batch
  - Too few will require many comparisons in the first stage
  - Too many will produce increase the number of expressions matched by the batch, requiring many comparisons in the second stage
- Since the expected matches function is quadratic, we are guaranteed a unimodal objective function (even for the multi-stage generalization).
Two-stage Optimization

Optimal Batch Size for Two-stage Zapp

$\mathbf{b}^* = 816$

501x reduction
Three-stage Optimization

2522x reduction
Results

- We have built a cost-effective, scalable search engine powered by CUDA.
- Need only two GTX580 GPUs to handle all tweets during peak load times.
  - Frees up a great deal of hardware and personnel resources for other purposes.
- Computational expense no longer increases linearly with number of expressions.
  - Now closer to $O(n^{2/3})$ instead of $O(n)$.
  - Difficult to pin down a firm figure due to model complexity and empirical assumptions.
Thank you!