# Bitwise Data Parallelism in Regular Expression Matching

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# Outline

# Acceleration of Regular Expression Matching

- Example: quickly find instances of `(^|[ ])\p{Lu}\p{Ll}+[.!?]($|[ ])` in text.
- Sequential algorithms use finite automata or backtracking.
- Parallelizing these approaches is difficult.
    - Finite state machines are the 13th (and hardest) "dwarf" in the Berkeley Landscape of Parallel Computing Research.
    - Embarassingly sequential?
    - Some success in parallel application of FSMs to multiple input streams.
    - Recent work shows some promise using techniques such as coalesced FSMs and principled speculation.

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- Uses bitstream addition for simultaneous nondeterministic matching of character class repetitions (MatchStar primitive).
- Compilation technologies for regular expressions (new), character classes (existing), unbounded bitstreams (existing).
- Recent work: all compilers integrated together with LLVM for fully dynamic regular expression matching.

# Bitwise Data Parallelism

- Parabix methods use a transform representation of text.
- Bitstreams are formed using one bit per input byte.
- Eight basis bit streams are defined for bit 0, bit 1, ... bit 7 of each byte.
- Perform bitwise processing with wide SIMD registers.
    - Process 128 bytes at a time with SSE2, Neon, Altivec.
    - Process 256 bytes at a time with AVX2.
- Transposition supported efficiently with SIMD pack operations.

# Impressive Results in Full Unicode Matching

- Find capitalized words at ends of sentences.
- Use Unicode upper/lower case categories.
- Match `(^|[ ])\p{Lu}\p{Ll}+[.!?]($|[ ])` against 110 MB Arabic file.
- `pcregrep` 14,772,797,548 CPU cycles.
- `egrep` 45,951,194,784 CPU cycles.
- `icgrep` (Parabix) 653,530,064 CPU cycles.
- 20X acceleration over `pcgregrep`, 70X over GNU `egrep`.

# Parallel Bit Streams: A Transform Representation of Text

- Given a byte-oriented character stream $T$, e.g., "`Ab17;`".
- Transpose to 8 parallel bit streams $b_0$, $b_1$, ..., $b_7$.
- Each stream $b_k$ comprises bit $k$ of each byte of $T$.

| $T$ | A | b | 1 | 7 | ; |
|---|---|---|---|---|---|
| ASCII | 01000001 | 01100010 | 00110001 | 00110111 | 00111011 |

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| $b_1$ | 1 | 1 | 0 | 0 | 0 |
| $b_2$ | 0 | 1 | 1 | 1 | 1 |
| $b_3$ | 0 | 0 | 1 | 1 | 1 |
| $b_4$ | 0 | 0 | 0 | 0 | 1 |
| $b_5$ | 0 | 0 | 0 | 1 | 0 |
| $b_6$ | 0 | 1 | 0 | 1 | 1 |
| $b_7$ | 1 | 0 | 1 | 1 | 1 |

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  - Character Class Compiler (CCC) produces stream equations from character classes.
  - Parallel Block Compiler (Pablo) converts unbounded stream programs to C++/SIMD.
  - Portable SIMD library for multiple architectures.

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  temp1 = (bit[1] &~ bit[0])
  temp2 = (bit[2] &~ bit[3])
  temp3 = (temp1 & temp2)
  temp4 = (bit[4] | bit[5])
  temp5 = (bit[7] &~ bit[6])
  temp6 = (temp5 &~ temp4)
  cc_a = (temp3 & temp6)
  ```
  ```

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- ```
  temp7 = (bit[0] | bit[1])
  temp8 = (bit[2] & bit[3])
  temp9 = (temp8 &~ temp7)
  temp10 = (bit[5] | bit[6])
  temp11 = (bit[4] & temp10)
  cc_0_9 = (temp9 &~ temp11)
  ```
  ```

# Character Class Common Subexpressions

- Multiple definitions use common subexpressions.
- CCC(`cc_z9 = [z9]`)
- ```
  temp12 = (bit[4] &~ bit[5])
  temp13 = (temp12 & temp5)
  temp14 = (temp9 & temp13)
  temp15 = (temp1 & temp8)
  temp16 = (bit[6] &~ bit[7])
  temp17 = (temp12 & temp16)
  temp18 = (temp15 & temp17)
  cc_z9 = (temp14 | temp18)
  ```
  ```

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- $M_i[j] = 1$ if and only if a match to the regular expression up to and including item $i$ in the expression occurs at position $j - 1$ in the input stream.
- Conceptually, marker streams are computed in parallel for all positions in the file at once (bitwise data parallelism).
- In practice, marker streams are computed block-by-block, where the block size is the size of a SIMD register in bits.

# Marker Stream Example

- Consider matching regular expression a[0-9]*[z9] against the input text below.

input data `a453z--b3z--az--a12949z--ca22z7--`

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- $M_1$ marks positions after occurrences of a.

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1..........1.....` |

# Marker Stream Example

- Consider matching regular expression `a[0-9]*[z9]` against the input text below.
- $M_1$ marks positions after occurrences of `a`.
- $M_2$ marks positions after occurrences of `a[0-9]*`.

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1.........1.....` |
| $M_2$ | `.1111........1...111111....111...` |

# Marker Stream Example

- Consider matching regular expression `a[0-9]*[z9]` against the input text below.
- $M_1$ marks positions after occurrences of `a`.
- $M_2$ marks positions after occurrences of `a[0-9]*`.
- $M_3$ marks positions after occurrences of `a[0-9]*[z9]`.

```
input data  a453z--b3z--az--a12949z--ca22z7--
M1          .1...........1...1.........1.....
M2          .1111........1...111111....111...
M3          .....1........1.....1.11......1..
```

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- Consider $M_2 = \text{MatchStar}(M_1, C)$

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1.........1.....` |
| $C = [0-9]$ | `.111....1.......11111.....11.1..` |

# Matching Character Class Repetitions with MatchStar

- $\text{MatchStar}(M, C) = (((M \wedge C) + C) \oplus C) \vee M$
- Consider $M_2 = \text{MatchStar}(M_1, C)$
- Use addition to scan each marker through the class.

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1.........1.....` |
| $C = [0\text{-}9]$ | `.111....1........11111.....11.1..` |
| $T_0 = M_1 \wedge C$ | `.1...............1.........1.....` |
| $T_1 = T_0 + C$ | `....1...1.............1......11..` |

# Matching Character Class Repetitions with MatchStar

- $\text{MatchStar}(M, C) = (((M \wedge C) + C) \oplus C) \vee M$
- Consider $M_2 = \text{MatchStar}(M_1, C)$
- Use addition to scan each marker through the class.
- Bits that change represent matches.

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1.........1.....` |
| $C = [0\text{–}9]$ | `.111....1........11111.....11.1..` |
| $T_0 = M_1 \wedge C$ | `.1...............1.........1.....` |
| $T_1 = T_0 + C$ | `....1...1.............1......11..` |
| $T_2 = T_1 \oplus C$ | `.1111............111111....111...` |

# Matching Character Class Repetitions with MatchStar

- $\text{MatchStar}(M, C) = (((M \wedge C) + C) \oplus C) \vee M$
- Consider $M_2 = \text{MatchStar}(M_1, C)$
- Use addition to scan each marker through the class.
- Bits that change represent matches.
- We also have matches at start positions in $M_1$.

| | |
|---|---|
| input data | `a453z--b3z--az--a12949z--ca22z7--` |
| $M_1$ | `.1...........1...1.........1.....` |
| $C = [0\text{–}9]$ | `.111....1........11111.....11.1..` |
| $T_0 = M_1 \wedge C$ | `.1...............1.........1.....` |
| $T_1 = T_0 + C$ | `....1...1.............1......11..` |
| $T_2 = T_1 \oplus C$ | `.1111............111111....111...` |
| $M_2 = T_2 \vee M_1$ | `.1111........1...111111....111...` |

# Regular Expression Compilation

- Our regular expression compiler produces unbounded Pablo code.
- RE_compile(a[0-9]*[z9])
- ```
  m0 = ~0
  m1 = pablo.Advance(m0 & cc_a)
  m2 = pablo.MatchStar(m1, cc_0_9)
  m3 = pablo.Advance(m2, cc_z9)
  ```
  ```

# Alternations and Optional Terms

- Most RE features are handled naturally.
- RE_compile(`a(b?|cd)`)
- 
```
m0 = ~0
m1 = pablo.Advance(m0 & cc_a)
m2 = pablo.MatchStar(m1, cc_b)
m3 = m1 | m2       # b is optional
m4 = pablo.Advance(m1, cc_c)
m5 = pablo.Advance(m2, cc_d)
m6 = m3 | m5       # two alternatives
```

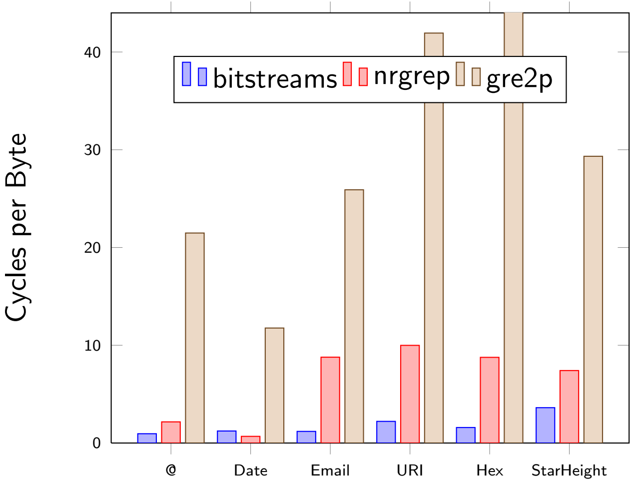
# Nested Repetitions Use While Loops

- While loops are used for complex or nested repetitions.
- RE_compile(`(a[0-9]*[z9])*`)
- 
```
m0 = ~0
t = m0   # while test variable
a = m0   # while result accumulator
while t:
   m1 = pablo.Advance(t & cc_a)
   m2 = pablo.MatchStar(m1, cc_0_9)
   m3 = pablo.Advance(m2, cc_z9)
   t = m3 &~ a   # iterate only for new matches
   a = a | m3
```

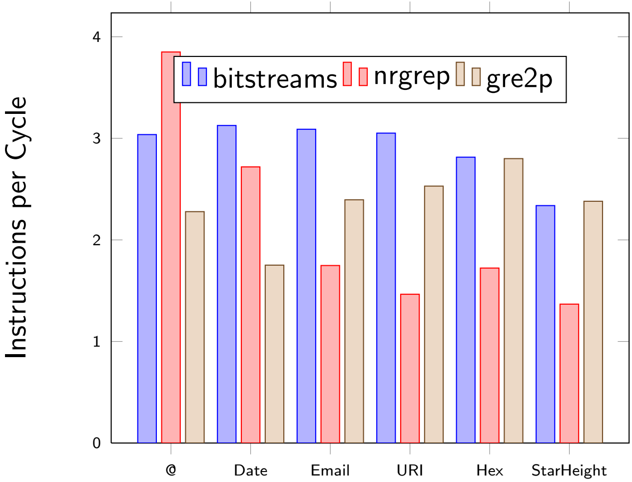
# Test Expressions

| Name | Expression |
|---|---|
| @ | `@` |
| Date | `([0-9][0-9]?)/([0-9][0-9]?)/([0-9][0-9]([0-9][0-9])?)` |
| Email | `([^ @]+)@([^ @]+)` |
| URI | `(([a-zA-Z][a-zA-Z0-9]*)://\|mailto:)([^ /]+)(/[^ ]*)?\|([^ @]+)@([^ @]+)` |
| Hex | `[ ](0x)?([a-fA-F0-9][a-fA-F0-9])+[.:,?! ]` |
| StarHeight | `[A-Z]((([a-zA-Z]*a[a-zA-Z]*[ ])*[a-zA-Z]*e[a-zA-Z]*[ ])*[a-zA-Z]*s[a-zA-Z]*[ ])*[.?!]` |

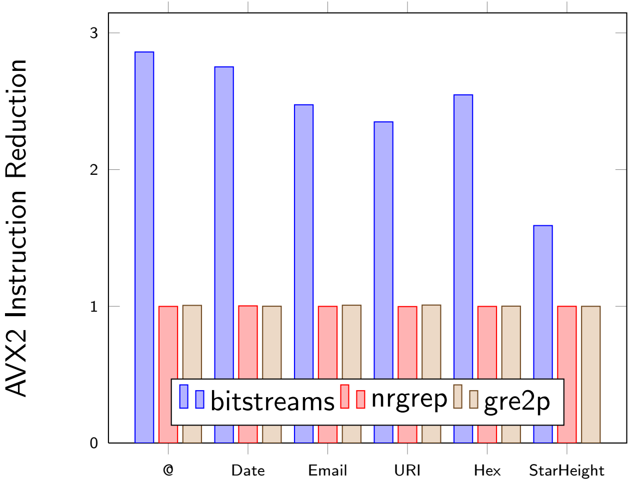
# SSE2 Performance



# IPC


Instructions per Cycle
bitstreams
nrgrep
gre2p
0
1
2
3
4
@
Date
Email
URI
Hex
StarHeight

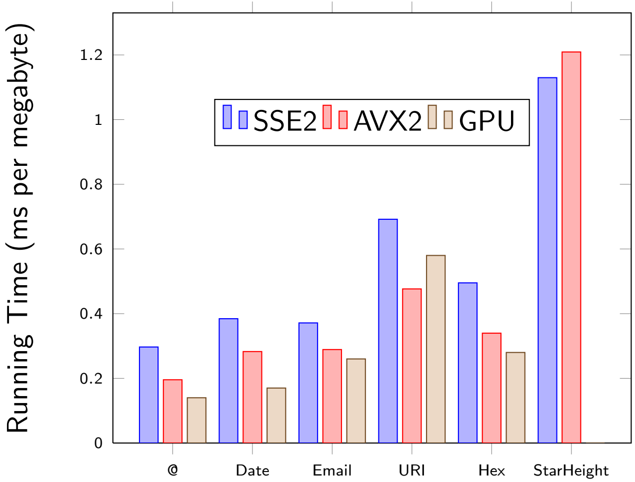
# SIMD Scalability



# Speedups Achieved

| Expression | Bitstream/AVX2 grep Speedup | | |
|---|---|---|---|
| | vs. nrgrep | vs. gre2p | vs. GNU grep -e |
| At | 3.5X | 34X | 1.6X |
| Date | 0.76X | 13X | 48X |
| Email | 9.5X | 28X | 12X |
| URI | 6.6X | 27X | 518X |
| Hex | 8.1X | 105X | 267X |
| StarHeight | 1.9X | 7.6X | 97X |

# GPU Performance



# Results

- A new class of parallel regular expression algorithms has been introduced based on the concept of bitwise data parallelism and MatchStar.
- Single core acceleration over sequential implementations can be dramatic.
- A long-stream addition technique has been developed to allow MatchStar to scale directly with SIMD instruction width.
- Perfect scaling in instruction count was observed with 256-bit AVX2 technology versus 128-bit SIMD technology except for nested repetition.
- GPU implementations show promise, but need additional work.

# Ongoing/Future Work

- The prototype technologies have now been re-implemented in a single C++ executable combining 4 compilers.
  - CCC: Character class compiler
  - RE_compile: regular expression compiler
  - Pablo: Block-at-a-time compiler
  - LLVM: Fully dynamic code generation.
- Compilation overhead is high, but tolerable for large files.
- Unicode support has been added, including additional MatchStar algorithms for variable-length Unicode character classes.
- Open source implementation available: `http://parabix.costar.sfu.ca/svn/icGREP/`