@hankadusikova

Regular Expressions

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Who am I?

- I live in Brno, Czechia.
- I'm a researcher at Avast.
- Organizer of Avast C++ Prague Meetup.
- (soon-ish) Czech national body to WG21.
- Amateur photographer and occasional hiker.

Let's talk about Regular Expressions...

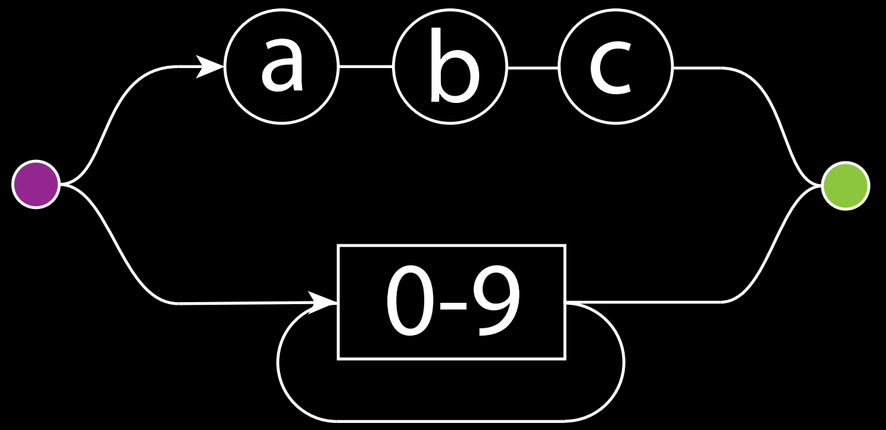
What can I do with a regular expression?*

- Match the subject against a pattern.
- Extract the content of the subject.
- Modify parts of the subject.

*Depending on algorithm used internally.

What does a regular expression look like*

abc|[0-9]+



*There are many slightly different dialects (Perl, ECMA, Posix).

How can I use regular expressions in C++?

```
// compile the RE only once
std::regex re{"abc|[0-9]+"};

bool match(std::string_view sv) {
  return std::regex_match(sv.begin(), sv.end(), re);
}
```

How can I use regular expressions in C?

```c
const unsigned char * p = "^[0-9]{4,16}?[aA]";
int err = 0;
size_t errOff = 0;

pcre2_code * re = pcre2_compile(p, PCRE2_ZERO_TERMINATED,
  0, &err, &errOff, NULL);

int match(const char * str, size_t sz) {
  return pcre2_match(re, str, sz, 0, 0, NULL, NULL);
}

// TODO: don't forget to call pcre2_code_free at the end ;)
```

What's going on in the constructor?

- Syntax parsing of the pattern.
- Building a data-structure (tree or table) representing the pattern.
- The calculations are very expensive (matching is not).

How can I avoid calling the constructor?

You can write a finite state machine by yourself.

But that's hard to write properly.
You can easily introduce an error.

You can use an external utility to generate the parser.

Really? There is no other way?

Compile Time Regular Expressions

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What do I want?

- Work with REs as with any other code.
- Don't pay any runtime cost for parsing the pattern.
- Have REs as quick as possible with zero-overhead.

How do I think REs should be used in C++?

```
bool match(std::string_view sv) noexcept {
   return std::regex_match<"abc|[0-9]+">(sv);
}
```

This is possible to implement with C++20's language support for Non Type Template Parameters.

The Compile Time Regular Expression library with C++20

```
bool match(std::string_view sv) noexcept {
   return ctre::match<"abc|[0-9]+">(sv);
}
```

Disabled for compilers without class NTTP support.

The Compile Time Regular Expression library with C++17

```
static constexpr ctre::fixed_string
   ptn = "abc|[0-9]+";

bool match(std::string_view sv) noexcept {
   return ctre::match<ptn>(sv);
}
```

The Compile Time Regular Expression library with C++17 and N3599 extension*

```
bool match(std::string_view sv) noexcept {
  using namespace ctre::literals;
  return "abc|[0-9]+"_ctre.match(sv);
}
```

Example: Constexpr

```
static_assert(
   ctre::match<"[0-9]+\\.[0-9]+">("123.456"sv)
);
```

Example: Constexpr

```
static_assert(
   ctre::match<"[0-9]+\\.([0-9]+)">("123.456"sv)
   .get<1>() == "456"sv
);
```

Example: Extracting a date from a string

```
struct date { unsigned year, month, day; };

std::optional<date> extract(std::string_view sv) noexcept {
  if (auto re = ctre::match<"(\\n+)/(\\n{1,2})/(\\n{1,2})">(sv)) {
    return date{
      conv(re.get<0>()),
      conv(re.get<1>()),
      conv(re.get<2>())
    };
  }
  return std::nullopt;
}
```

Example: Extracting a name from a CSV-like input

```
struct name { std::string_view first, family; };

std::optional<name> extract(std::string_view sv) noexcept {
  if (auto [re,f,l] = ctre::match<"([A-Za-z]++),([A-Za-z]++)">(sv); re) {
    return name{f,l};
  } else {
    return std::nullopt;
  }
}
```

But this must generate horrible assembly!

Not really :)

Optimized assembly is just 68 LoC long!

A ▾ Save/Load + Add new... ▾ C++ ▾

```
1  #include <ctre.hpp>
2  #include <string_view>
3  #include <optional>
4
5  struct name { std::string_view first, family; };
6
7  static constexpr ctll::basic_fixed_string pattern = "([A-Za-z]++),([A-Za-z]++)";
8
9  std::optional<name> extract(std::string_view sv) noexcept {
10     if (auto [re,f,l] = ctre::re<pattern>().match(sv); re) {
11         return name{f,l};
12     } else {
13         return std::nullopt;
14     }
15 }
16
```

x86-64 gcc 7.3 ▾ -std=c++17 -O3

A ▾ 11010 .LX0: .text // \s+ Intel Demangle Libraries ▾ + Add new... ▾ Add tool... ▾

```
1  extract(std::basic_string_view<char, std::char_traits<char> >):
2          add     rsi, rdx
3          mov     rax, rdi
4          cmp     rdx, rsi
5          je      .L2
6          movzx   ecx, BYTE PTR [rdx]
7          and     ecx, -33
8          sub     ecx, 65
9          cmp     cl, 25
10         jbe     .L15
11 .L2:
12         xor     edx, edx
13         mov     BYTE PTR [rax+32], dl
14         ret
15 .L15:
16         lea     rcx, [rdx+1]
17         cmp     rsi, rcx
18         je      .L2
19 .L5:
20         movzx   r9d, BYTE PTR [rcx]
21         mov     r8d, r9d
22         and     r8d, -33
23         sub     r8d, 65
24         cmp     r8b, 25
25         jbe     .L3
26         cmp     rsi, rcx
27         je      .L2
28         cmp     r9b, 44
29         jne     .L2
30         lea     r9, [rcx+1]
31         cmp     rsi, r9
32         je      .L2
33         movzx   edi, BYTE PTR [rcx+1]
34         and     edi, -33
35         sub     edi, 65
36         cmp     dil, 25
37         ja      .L2
38         lea     r8, [rcx+2]
39         cmp     rsi, r8
40         je      .L8
41 .L9:
42         movzx   edi, BYTE PTR [r8]
43         and     edi, -33
44         sub     edi, 65
45         cmp     dil, 25
```

(In theory) The optimizer should be able to see the same intent with std::regex **too...**

Unfortunately it doesn't.

The equivalent code is ~19.7 kLoC.

A Save/Load + Add new... C++

```cpp
#include <regex>
#include <string_view>
#include <optional>

struct name { std::string_view first, family; };

std::optional<name> extract(std::string_view sv) noexcept {
    static std::regex re{"^([a-z]++),([a-z]++)$"};

    std::match_results<std::string_view::iterator> results;

    if (std::regex_match(sv.begin(), sv.end(), results, re)) {
        //[[assert: results.size() == 2]];
        return name{results[0].str(), results[1].str()};
    } else {
        return std::nullopt;
    }
}
```

x86-64 gcc 7.3 -std=c++17 -O3

A 11010 .LX0: .text // \s+ Intel Demangle Libraries + Add new... Add tool...

```
std::ctype<char>::do_widen(char) const:
        mov     eax, esi
        ret
std::ctype<char>::do_narrow(char, char) const:
        mov     eax, esi
        ret
std::_Function_base::_Base_manager<std::__detail::_AnyMatcher<std::__cxx11::regex_traits<char>, fal
        test    edx, edx
        je      .L6
        cmp     edx, 1
        jne     .L5
        mov     QWORD PTR [rdi], rsi
.L5:
        xor     eax, eax
        ret
.L6:
        mov     QWORD PTR [rdi], OFFSET FLAT:typeinfo for std::__detail::_AnyMatcher<std::__cxx11::
        xor     eax, eax
        ret
std::_Function_base::_Base_manager<std::__detail::_AnyMatcher<std::__cxx11::regex_traits<char>, fal
        cmp     edx, 1
        je      .L10
        jb      .L11
        cmp     edx, 2
        jne     .L9
        mov     rax, QWORD PTR [rsi]
        mov     QWORD PTR [rdi], rax
.L9:
        xor     eax, eax
        ret
.L11:
        mov     QWORD PTR [rdi], OFFSET FLAT:typeinfo for std::__detail::_AnyMatcher<std::__cxx11::
        xor     eax, eax
        ret
.L10:
        mov     QWORD PTR [rdi], rsi
        xor     eax, eax
        ret
std::_Function_base::_Base_manager<std::__detail::_AnyMatcher<std::__cxx11::regex_traits<char>, fal
        cmp     edx, 1
        je      .L15
        jb      .L16
        cmp     edx, 2
        jne     .L14
        mov     rax, QWORD PTR [rsi]
```

What about errors?

```
static inline constexpr ctre::fixed_string pattern = ")hello";

bool fnc(std::string_view view) {
  return ctre::match<pattern>(view);
}
```

```
In file included from test.cpp:1:
In file included from include/ctre.hpp:5:
include/ctre/functions.hpp:48:2: error: static_assert failed due to requirement 'correc
        static_assert(correct, "Regular Expression contains syntax error.");
        ^             ~~~~~~~
test.cpp:21:15: note: in instantiation of function template specialization 'ctre::match
        return ctre::match<pattern>(view);
                   ^
```

Compile Time Regular Expression library

- is easy to use,
- uses existing and well known RE syntax,
- is perfect for checking inputs of your program,
- emits nice assembly,
- works on Clang and GCC and MSVC 15.8.8+
- and we will talk later about performance...

The Parser

Disclaimer: all examples were simplified.

How does it work?

- It uses a generic LL(1) parser for converting a pattern into a type.
- The parser uses a provided PCRE compatible grammar.
- Output type encodes the pattern as an expression template.
- Evaluation of the expression template matches the subject.

How does the LL(1) parser work?

- Starts with a start symbol on the stack.
- On every step it pops one symbol from the stack and checks the current character at the input.
- Based on the pair of symbol and character it decides to:
  - push a string of symbols to the stack,
  - pop a character from the input,
  - or reject.
- Repeat until the stack and input are empty then accept.

Let's create RE grammar...

What does the grammar look like?

f(*symbol*,*char*) →

	(	)	*	+	?	\	a	d	|	other	ϵ
→ ***S***	(*alt0*) *mod seq alt*					\ *esc mod seq alt*	a *mod seq alt*	d *mod seq alt*		other *mod seq alt*	ϵ
alt0	(*alt0*) *mod seq alt*					\ *esc mod seq alt*	a *mod seq alt*	d *mod seq alt*		other *mod seq alt*	
alt		ϵ							| *seq0 alt*		ϵ
esc							a	d			
mod	ϵ	ϵ	*	+	?	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ
seq0	(*alt0*) *mod seq*					\ *esc mod seq*	a *mod seq*	d *mod seq*		other *mod seq*	
seq	(*alt0*) *mod seq*	ϵ				\ *esc mod seq*	a *mod seq*	d *mod seq*	ϵ	other *mod seq*	ϵ
(	pop										
)		pop									
*			pop								
+				pop							
?					pop						
\						pop					
a							pop				
d								pop			
|									pop		
other										pop	
Z_0											accept

How can I write it in C++?

How can I represent symbols in C++?

```
struct S {};
struct alt0 {};
struct alt {};
struct esc {};
struct mod {};
struct seq0 {};
struct seq {};

using start_symbol = S;
```

How can I represent an LL(1) table in C++?

```
//    f(symbol, char) → (...)
auto f(symbol, term<'c'>) -> list{...};

//    f(symbol, symbol) → pop input
template <auto S> auto f(term<S>, term<S>) -> pop_input;

//    f(symbol, char) → reject
auto f(...) -> reject;

//    f(Z0, ϵ) → accept
auto f(empty_stack, epsilon) -> accept;
```

How can I pass the grammar?

```
struct my_grammar {
  struct S {};
  struct alt0 {};
  struct alt {};
  // ...

  using start_symbol = S;

  auto f(...) -> reject;
  // ...
}
```

Let's use it...

```
constexpr bool ok = parser<my_grammar, "^hello">::correct;
```

What about parser?

```
template <typename Grammar, ...> struct parser {
  //...
  auto next_move = Grammar::f(top_of_stack, current_char);
  //...
}
```

How do I get current character?

```
template <..., fixed_string Str> struct parser {
  // ...
  template <size_t Pos> constexpr auto get_character() const {
    if constexpr (Pos < Str.size()) return term<Str[Pos]>{};
    else return epsilon{};
  }
  // ...
};
```

How do I implement the input string?

```
template <typename CharT, size_t N> struct fixed_string {
  std::array<CharT, N> data;
  // constexpr constructor from const char[N]

  constexpr auto operator[](size_t i) const noexcept { return data[i]; }
  constexpr size_t size() const noexcept { return N; }
  constexpr auto operator<=>(const fixed_string &) = default;
};

template <typename CharT, size_t N>
 fixed_string(const CharT[N]) -> fixed_string<CharT, N>;

// more info about class NTTP in p0732 by Jeff Snyder and Louis Dionne
```

How do I implement the stack?

```
template <typename... Ts> struct list { };

template <typename... Ts, typename... As>
 constexpr auto push(list<Ts...>, As...) -> list<As..., Ts...>;

template <typename T, typename... As>
 constexpr auto pop(list<T, Ts...>) -> list<Ts...>;

template <typename T, typename... Ts>
 constexpr auto top(list<T, Ts...>) -> T;

struct empty { };
constexpr auto top(list<>) -> empty;
```

How does it fit together?

```
constexpr bool ok = parser<my_grammar, "there$">::correct;
```

```
template <typename Grammar, fixed_string Str> struct parser {
  static constexpr bool correct = parse(list<Grammar::start_symbol>());

  // prepare each step and move to next
  template <size_t Pos = 0, typename S>
   static constexpr bool parse(S stack) {

    using next_stack = decltype(  pop(stack)                          );
    using symbol     = decltype(  top(stack)                          );
    using current    = decltype(  get_character<Pos>()                );
    using next_move  = decltype(  Grammar::f(symbol{}, current{})     );
    return move<Pos>(next_move{}, next_stack{});
  }
  //...
```

```
// pushing something to stack (epsilon case included)
template <size_t Pos, typename... Push, typename Stack>
 static constexpr bool move(list<Push...>, Stack stack) {
  using next_stack = decltype(  push(stack, Push{}...)  )
  return parse<Pos>(next_stack{});
}

// move to next character
template <size_t Pos, typename Stack>
 static constexpr bool move(pop_input, Stack stack) {
  return parse<Pos+1>(stack);
}
```

```
template <size_t Pos, typename Stack>
 static constexpr bool move(reject, Stack) {
  return false;
}

template <size_t Pos, typename Stack>
 static constexpr bool move(accept, Stack) {
  return true;
}

}; // end of Parser struct
```

But this is returning a boolean value! Is there something missing?

Building
The Expression Template

How can I build a type from a string?

Where are the semantic actions placed?

	(	)	*	+	?	\	a	d	|	other	ϵ
→ ***S***	(*alt0*) *mod seq alt*					\ *esc mod seq alt*	a **char** *mod seq alt*	d **char** *mod seq alt*		other **char** *mod seq alt*	ϵ
alt0	(*alt0*) *mod seq alt*					\ *esc mod seq alt*	a **char** *mod seq alt*	d **char** *mod seq alt*		other **char** *mod seq alt*	
alt		ϵ							| *seq0* **alt** *alt*		ϵ
esc							a **alpha**	d **digit**			
mod	ϵ	ϵ	* **star**	+ **plus**	? **opt**	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ
seq0	(*alt0*) *mod seq*					\ *esc mod seq*	a **char** *mod seq*	d **char** *mod seq*		other **char** *mod seq*	
seq	(*alt0*) *mod* **seq** *seq*	ϵ				\ *esc mod* **seq** *seq*	a **char** *mod* **seq** *seq*	d **char** *mod* **seq** *seq*	ϵ	other **char** *mod* **seq** *seq*	ϵ
(	pop										
)		pop									
*			pop								
+				pop							
?					pop						
\						pop					
a							pop				
d								pop			
|									pop		
other										pop	
Z_0											accept

What do the SemanticAction symbols look like?

```
struct my_grammar {
   struct _char: action {};
   struct alpha: action {};
   struct digit: action {};
   struct seq: action {};
   struct star: action {};
   struct plus: action {};
   struct opt: action {};
   // ...
}
```

What are the changes in the parser?

```
template <typename Grammar, fixed_string Str> struct parser {

  template <size_t Pos = 0, typename S, typename T = list<>>
   static constexpr auto parse(S stack, T subject = {}) {
    using next_stack = decltype(  pop(stack)  );
    using symbol     = decltype(  top(stack)  );
    if constexpr (SemanticAction<symbol>) {
      using previous = decltype(  prev_character<Pos>()  );
      using next_subject = decltype( modify(symbol{}, previous{}, subject) );
      return parse<Pos>(next_stack(), next_subject{});
    } else {
      using current    = decltype(  get_character<Pos>()              );
      using next_move  = decltype(  Grammar::f(symbol{}, current{})  );
      return move<Pos>(next_move{}, next_stack{}, subject);
    }
  }
```

```
// pushing something to stack (epsilon case included)
template <size_t Pos, typename... Push, typename Stack, typename T>
 static constexpr auto move(list<Push...>, Stack stack, T subject) {
  using next_stack = decltype(  push(stack, Push{}...)  )
  return parse<Pos>(next_stack{}, subject);
}

// move to next character
template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(pop_input, Stack stack, T subject) {
  return parse<Pos+1>(stack, subject);
}
```

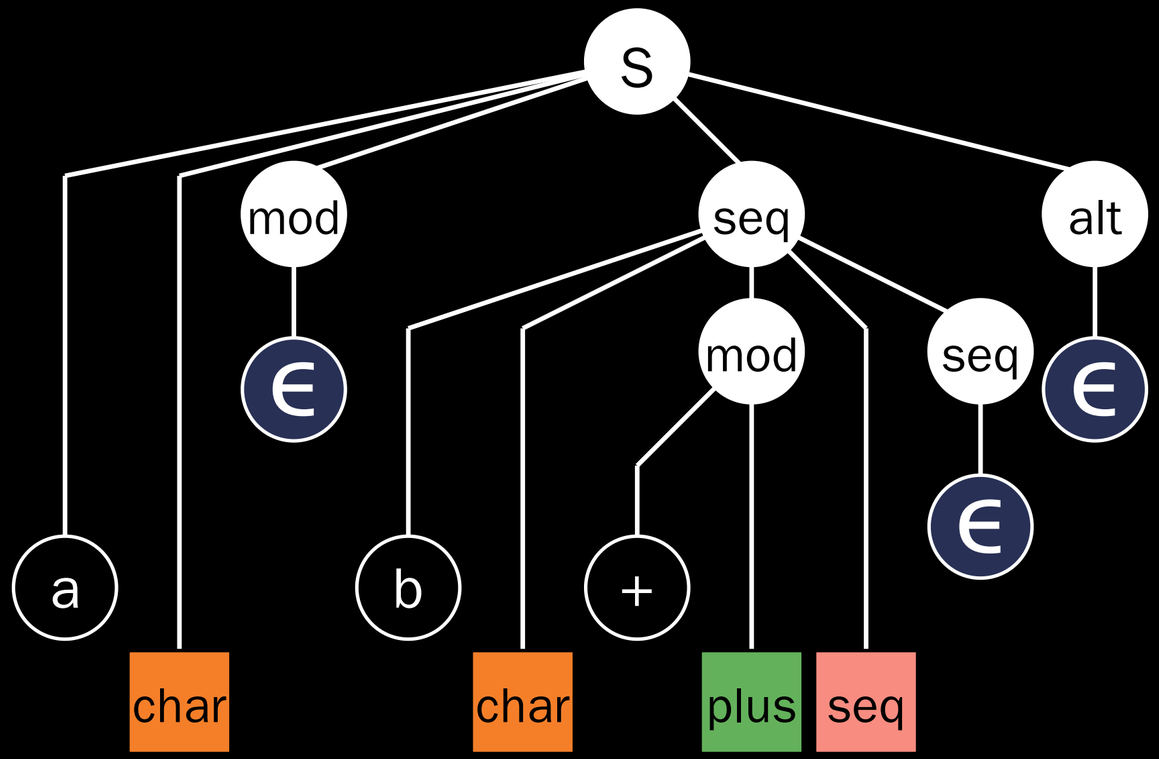
```
template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(reject, Stack, T subject) {
  return pair{false, subject};
}

template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(accept, Stack, T subject) {
  return pair{true, subject};
}

}; // end of Parser struct
```

Where is my subject?

```
template <typename Grammar, fixed_string Str> struct parser {
  static constexpr pair result
    = parse(list<Grammar::start_symbol>(), list<>());
  static constexpr auto correct = result.first;
  static_assert(correct, "RE syntax error");
  using output_type = decltype(front(result.second));
  // ...
};

using T = parser<my_grammar, "^wow$">::output_type;
```

What does building from a string look like?

ab+




```
seq<ch<'a'>,plus<ch<'b'>>>
```

What about the modify function?

Pushing character

```
template <auto C, typename... Ts>
 auto modify(my_grammar::_char, term<C>, list<Ts...>)
  -> list<ch<C>, Ts...>;
```

(Notice the term and ch types.)

Making something optional

```
template <auto C, typename Opt, typename... Ts>
 auto modify(my_grammar::opt, term<C>, list<Opt, Ts...>)
  -> list<opt<Opt>, Ts...>;
```

Making cycles

```
template <auto C, typename Plus, typename... Ts>
 auto modify(my_grammar::plus, term<C>, list<Plus, Ts...>)
  -> list<plus<Plus>, Ts...>;
```

```
template <auto C, typename Star, typename... Ts>
 auto modify(my_grammar::star, term<C>, list<Star, Ts...>)
  -> list<star<Star>, Ts...>;
```

Creating a sequence

```
template <auto C, typename A, typename B, typename... Ts>
 auto modify(my_grammar::seq, term<C>, list<B, A, Ts...>)
  -> list<seq<A, B>, Ts...>;
```

(Notice the switched order of A & B on the stack.)

Adding to a sequence

```
template <auto C, typename... As, typename B, typename... Ts>
 auto modify(my_grammar::seq, term<C>, list<B, seq<As...>, Ts...>)
  -> list<seq<As..., B>, Ts...>;
```

Making an alternate

```
template <auto C, typename A, typename B, typename... Ts>
 auto modify(my_grammar::alt, term<C>, list<B, A, Ts...>)
  -> list<alt<A, B>, Ts...>;
```

(Notice the switched order of A & B on the stack.)

Adding to an alternate

```
template <auto C, typename... As, typename B, typename... Ts>
 auto modify(my_grammar::alt, term<C>, list<B, alt<As...>, Ts...>)
  -> list<alt<As..., B>, Ts...>;
```

Adding a digit or alpha class

```
template <auto C, typename... Ts>
 auto modify(my_grammar::alpha, term<C>, list<Ts...>)
  -> list<alpha, Ts...>;
```

```
template <auto C, typename... Ts>
 auto modify(my_grammar::digit, term<C>, list<Ts...>)
  -> list<digit, Ts...>;
```

We have the expression template.

```
static_assert(std::is_same_v<
   seq<ch<'a'>,plus<ch<'b'>>>,
   parser<my_grammar,"ab+">::output_type
>);
```

Evaluating
The Expression Template

Let's make this work...

```
match<"\\a\\d+">("a42"sv);
```

How are REs matched against a string?

```
template <fixed_string re> bool match(std::string_view sv) {
  static_assert(parser<my_grammar, re>::correct);
  using RE = parser<my_grammar, re>::output_type;

  return match(sv.begin(), sv.begin(), sv.end(), list<RE>{}).success;
}
```

List? Again?!

Yes!

But first what's the output type of match(...)?

```
template <ForwardIterator It> struct result {
  ForwardIterator it;
  bool success;
  // constexpr constructor etc...
};
```

Matching a character

```
template <ForwardIterator It, auto C, typename... Ts>
 result<It> match(It begin, It it, It end, list<ch<C>, Ts...>) {

  if (it == end) return {it, false};
  if (*it != C) return {it, false};

  return match(begin, std::next(it), end, list<Ts...>{});
}
```

Matching an alpha or a digit class

```
template <ForwardIterator It, typename... Ts>
 result<It> match(It begin, It it, It end, list<digit, Ts...>) {
  if (it == end) return {it, false};
  if (!(*it >= '0' && *it <= '9')) return {it, false};
  return match(begin, std::next(it), end, list<Ts...>{});
}
```

```
template <ForwardIterator It, typename... Ts>
 result<It> match(It begin, It it, It end, list<alpha, Ts...>) {
  if (it == end) return {it, false};
  if (!(*it >= 'a' && *it <= 'z')) return {it, false};
  return match(begin, std::next(it), end, list<Ts...>{});
}
```

Matching a sequence

```
template <ForwardIterator It, typename... Seq, typename... Ts>
 result<It> match(It begin, It it, It end, list<seq<Seq...>, Ts...>)

  return match(begin, it, end, list<Seq..., Ts...>{});
}
```

Matching an optional

```
template <ForwardIterator It, typename... Opt, typename... Ts>
 result<It> match(It begin, It it, It end, list<opt<Opt...>, Ts...>)

  if (auto out = match(begin, it, end, list<Opt..., Ts...>{})) {
    return out;
  } else {
    // try it without the content of opt<...>
    return match(begin, it, end, list<Ts...>{}));
  }
}
```

Matching an alternate

```
template <ForwardIterator It, typename Head, typename... Tail, typename... Ts>
 result<It> match(It begin, It it, It end, list<alt<Head, Tail...>, Ts...>) {
  if (auto out = match(begin, it, end, list<Head, Ts...>{})) {
    return out;
  } else {
    // try the next one
    return match(begin, it, end, list<alt<Tail...>, Ts...>{}));
  }
}

template <ForwardIterator It, typename... Ts>
 result<It> match(It begin, It it, It end, list<alt<>, Ts...>) {
  // no option from alternation was successful
  return {it, false};
}
```

Matching a plus cycle

```
template <ForwardIterator It, typename First, typename... Alt, typename... Ts>
 result<It> match(It begin, It it, It end, list<plus<Plus...>, Ts...>) {
  for (;;) {
    if (auto inner = match(begin, it, end, list<Plus..., end_of_cycle>{})) {
      if (auto out = match(begin, it, end, list<Ts...>{})) {
        return out;
      } else {
        it = inner.it;
      }
    } else return {it, false};
  }
}
```

```
struct end_of_cycle {};

template <ForwardIterator It>
 result<It> match(It, It it, It, list<end_of_cycle>) {
  return {it, true};
}
```

(The cycle is lazy.)

Matching a star cycle

```
template <ForwardIterator It, typename First, typename... Alt, typename... Ts>
 result<It> match(It begin, It it, It end, list<star<Star...>, Ts...>) {
  for (;;) {
    if (auto out = match(begin, it, end, list<Ts...>{})) {
      return out;
    } else if (auto inner = match(begin, it, end, list<Star..., end_of_cycle>{})) {
      if (auto out = match(begin, it, end, list<Ts...>{})) {
        return out;
      } else {
        it = inner.it;
      }
    } else return {it, false};
  }
}
```

(The cycle is lazy.)

How do we know it's the end?

```
// and at the end... we need to check for the end :)
template <ForwardIterator It>
 result<It> match(It begin, It it, It end, list<>{}) {
  // if we are at the end input we should accept
  return {it, it == end};
}
```

(Helper for finishing the regex matching.)

In the examples there are no captures or any advanced RE functionality.

Benchmarks

How quick or slow is this thing?

Measured code (grep-like utility)

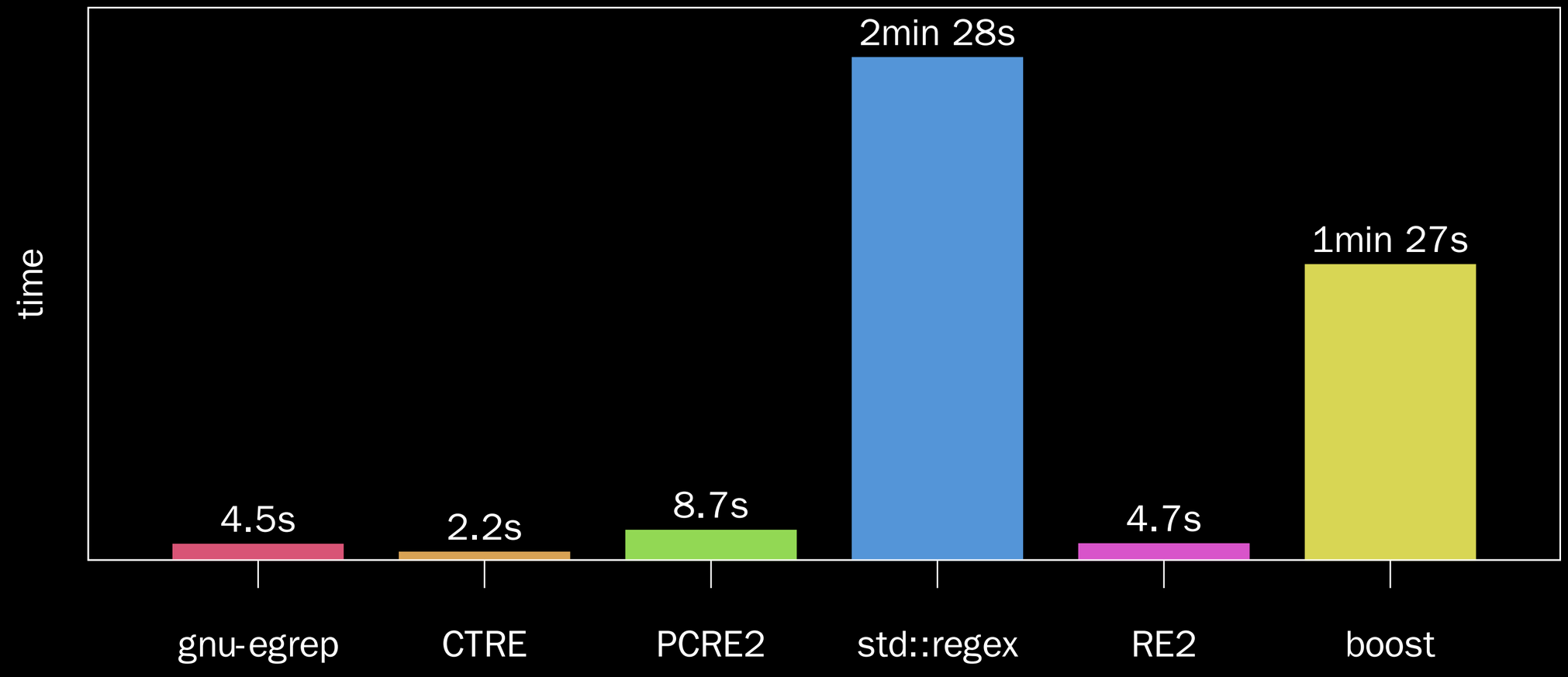
```
int main(int argc, char ** argv) {
  auto re = PREPARE("PATTERN");
  std::ifstream stream{argv[1], std::ifstream::in};
  std::string line;
  while (std::getline(stream, line)) {
    if (re.MATCH(line)) {
      std::cout << line << '\n';
    }
  }
}
```

Measurement methodology

- CSV file (1.3 GiB) with 6.5 MLoC
- Median of 3 measurements
- MacBook Pro 13" 2016 i7 3.3Ghz

Runtime Matching (GCC, Linux): `ABCD|DEFGH|EFGHI|A{4,}`

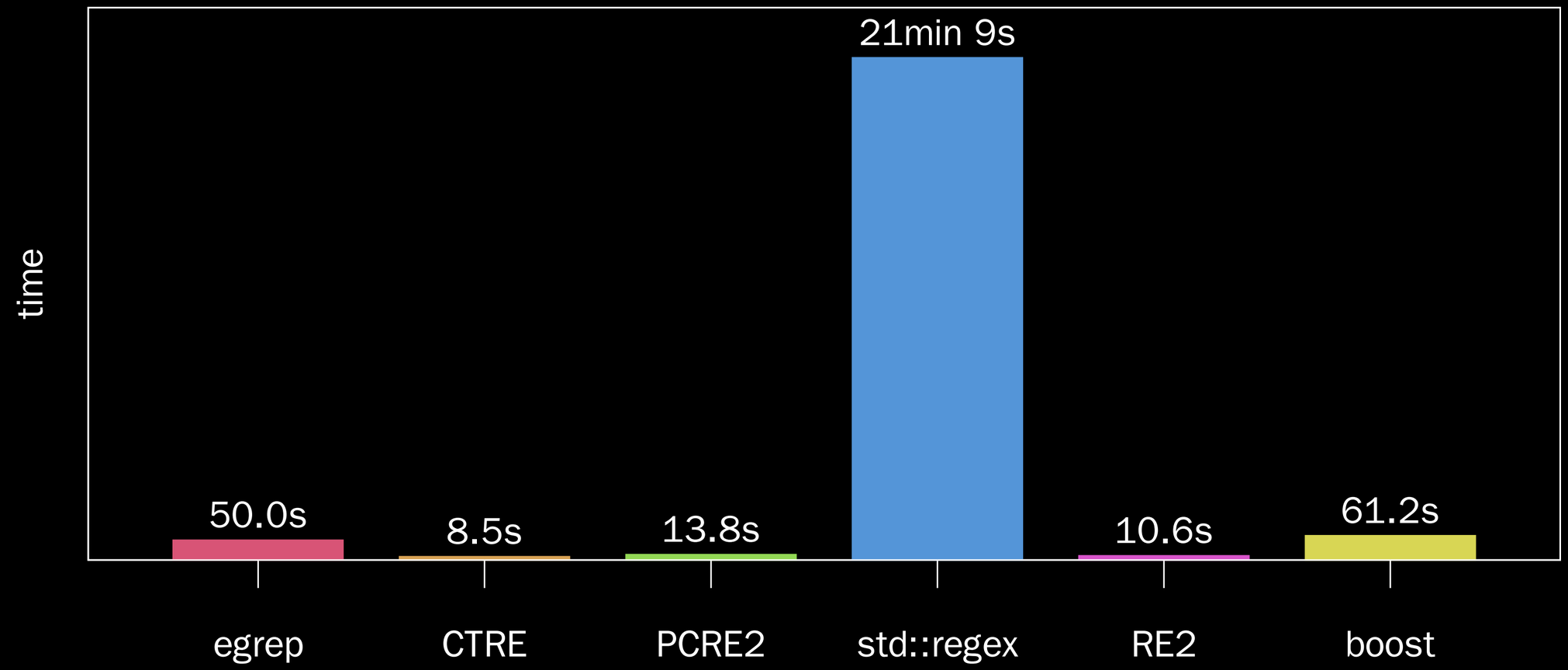
Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).



(less is better)

Runtime Matching (Clang, Mac): `ABCD|DEFGH|EFGHI|A{4,}`

Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).

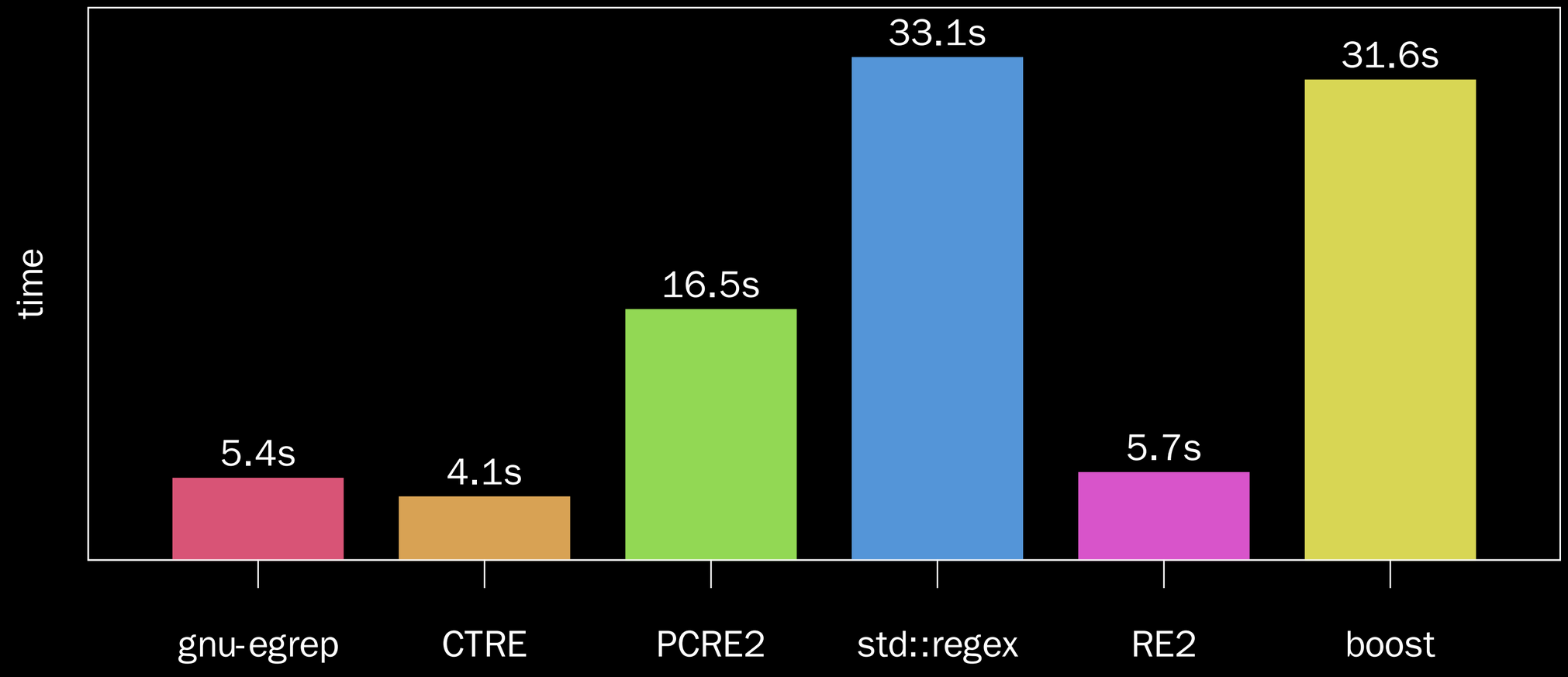


(less is better)

Looks like std::regex in libc++ is slow...

Runtime Matching (GCC, Linux): `[0-9a-fA-F]{8,16}`

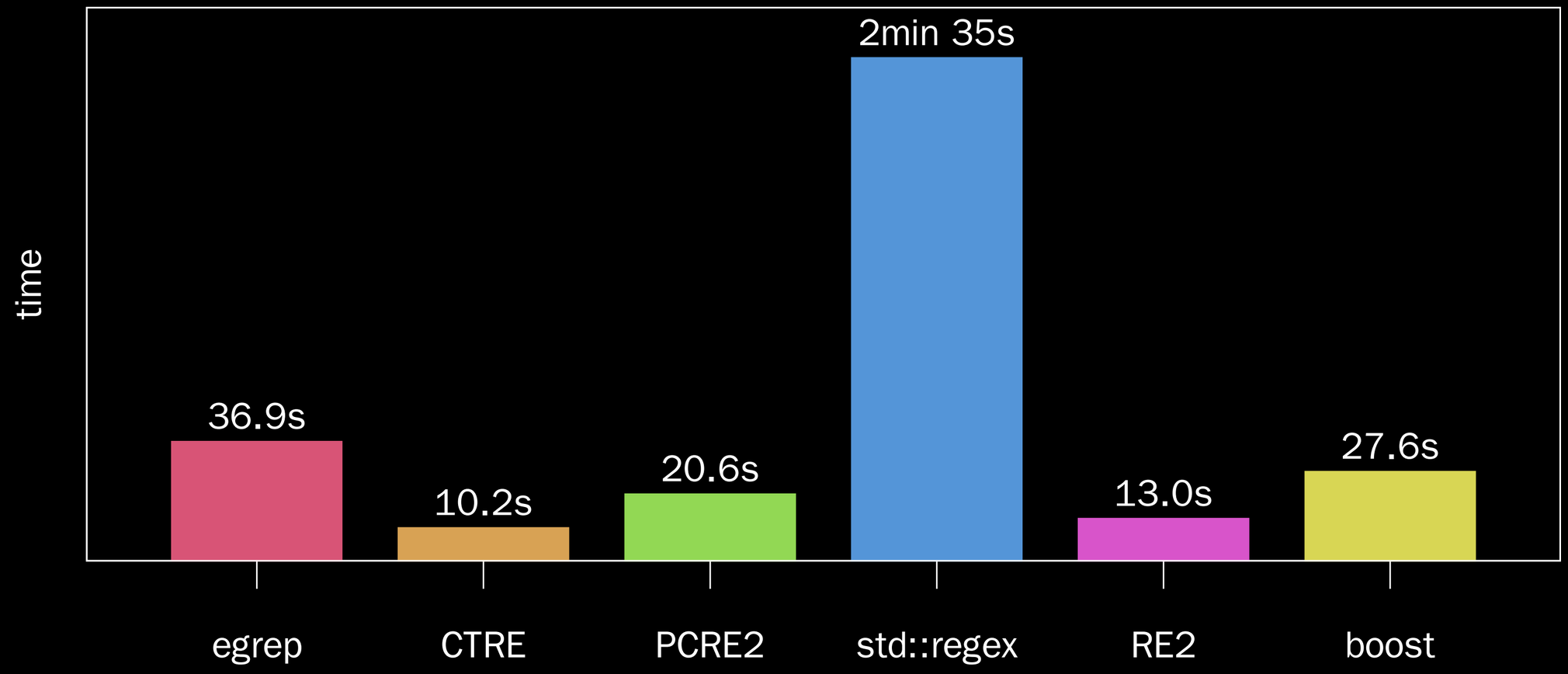
Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).



(less is better)

Runtime Matching (Clang, Mac): `[0-9a-fA-F]{8,16}`

Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).

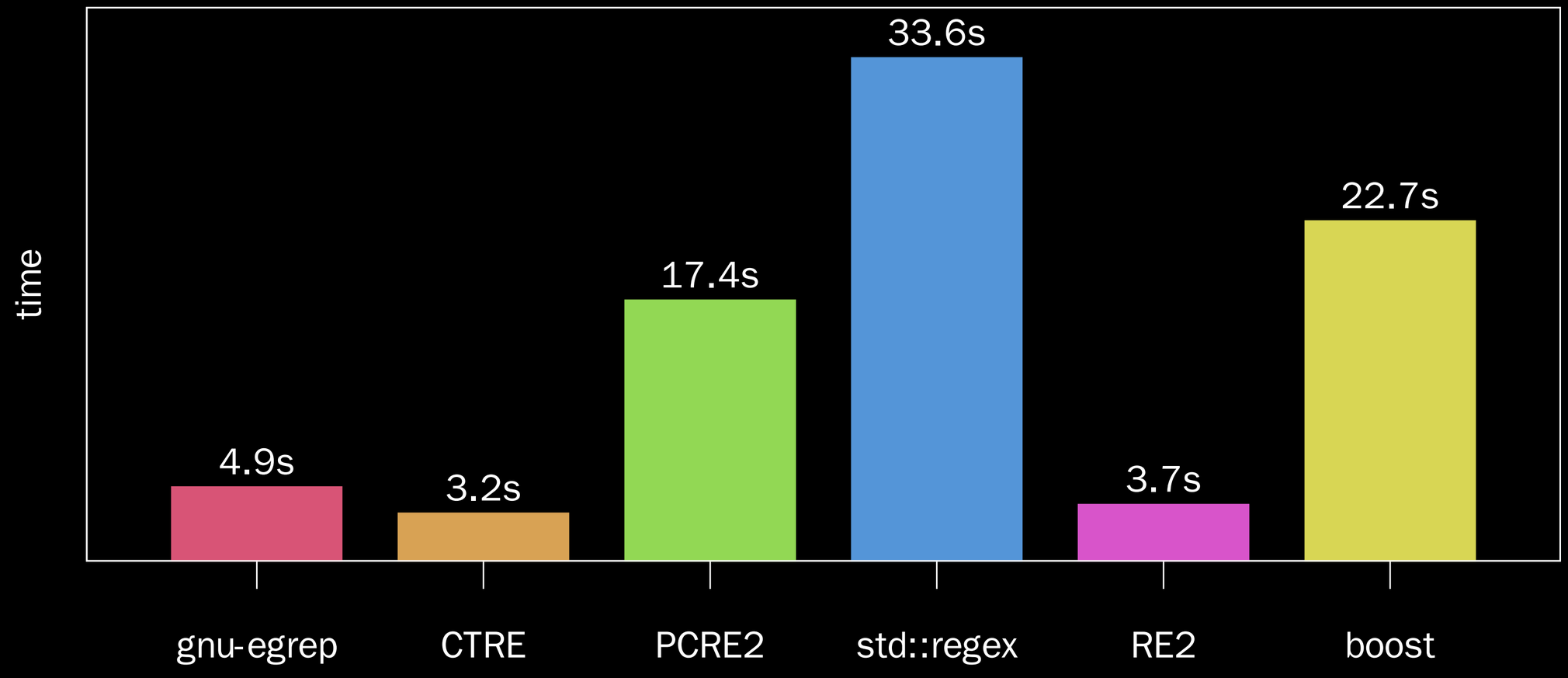


(less is better)

So the std::regex in libc++ is consistently bad.

Runtime Matching (GCC, Linux): `([0-9]{4,16})?[aA]`

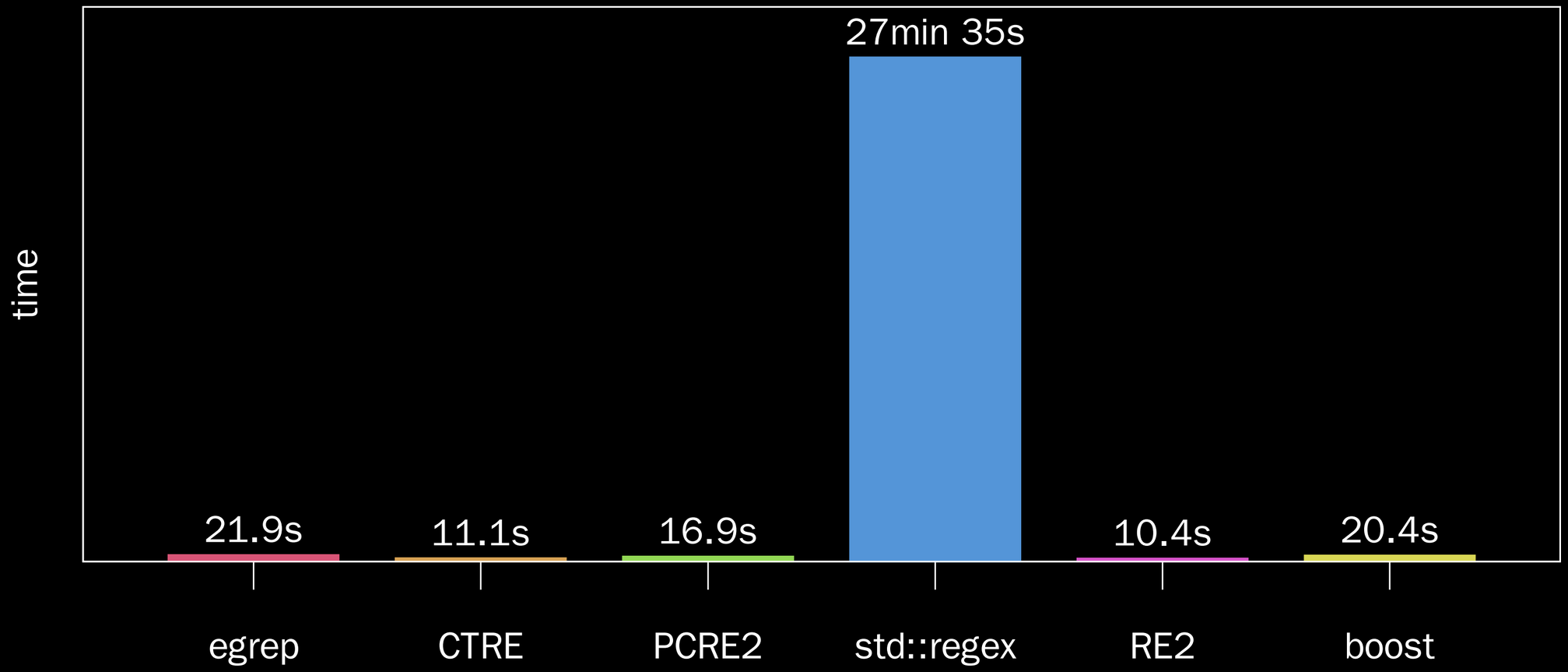
Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).



(less is better)

Runtime Matching (Clang, Mac): `([0-9]{4,16})?[aA]`

Matching pattern against Big CSV file (1.3 GiB, 6.5 MLoC).



(less is better)

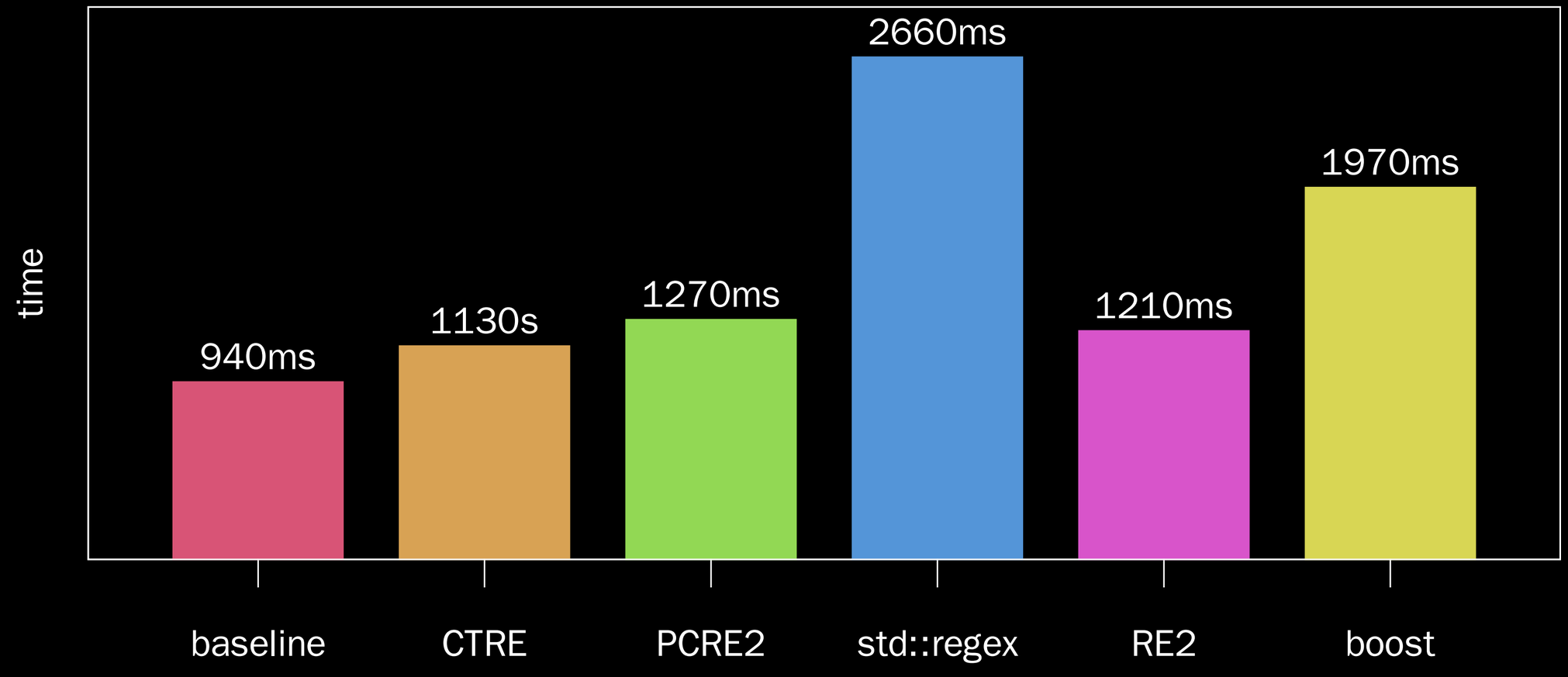
Something interesting...

Compile Time Benchmark

- All tests include the same set of headers.
- I measured compilation time only, without linking.

Optimized Compile Time of The Benchmark code.

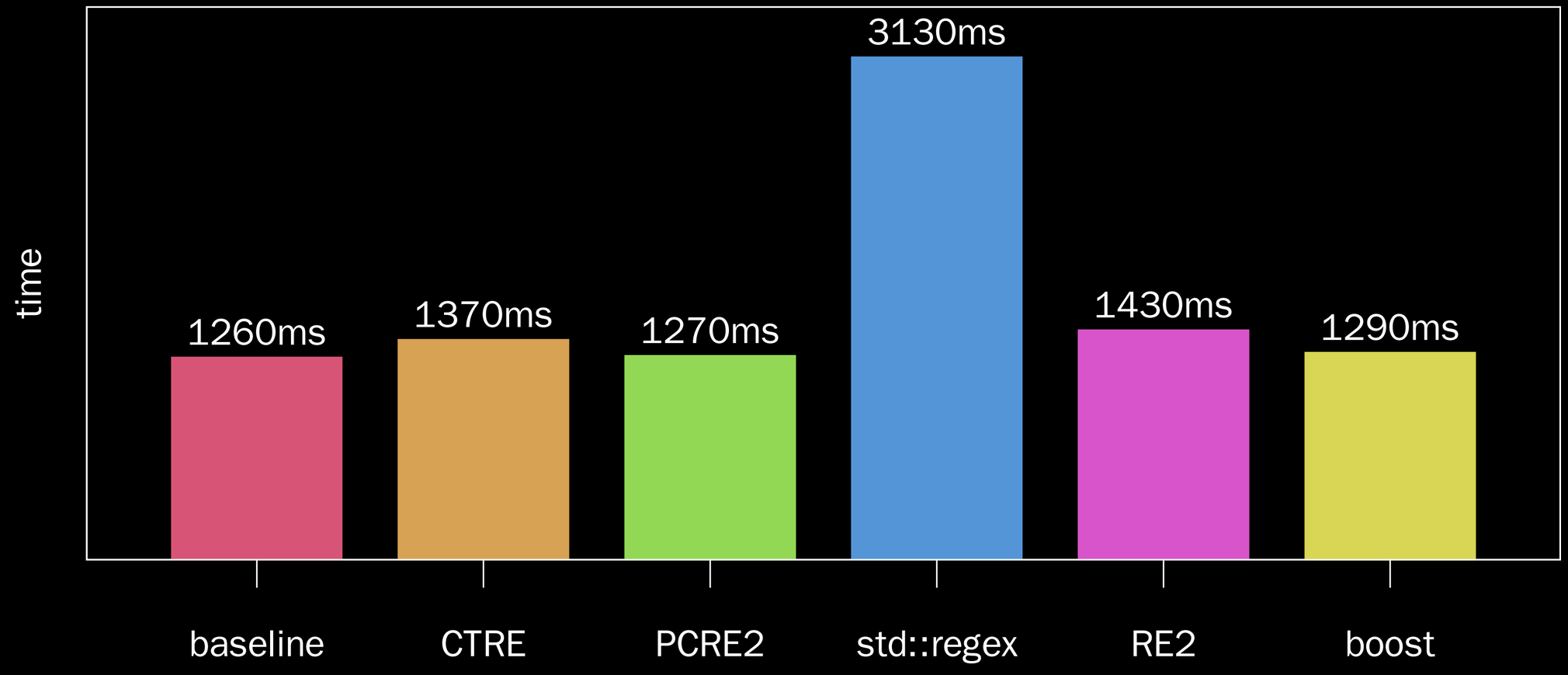
`clang -c -O3`



(less is better)

Optimized Compile Time of The Benchmark code.

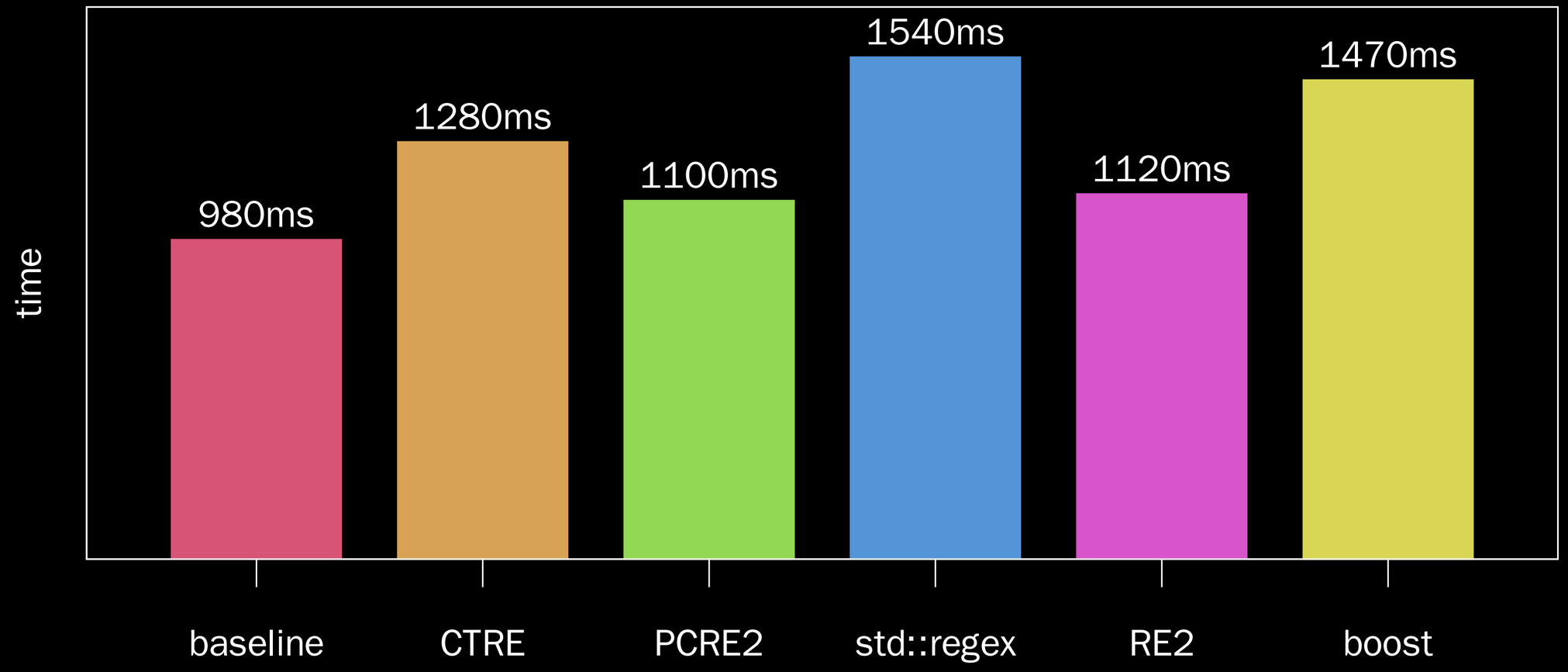
`gcc -c -O3`



(less is better)

Compile Time of The Benchmark code.

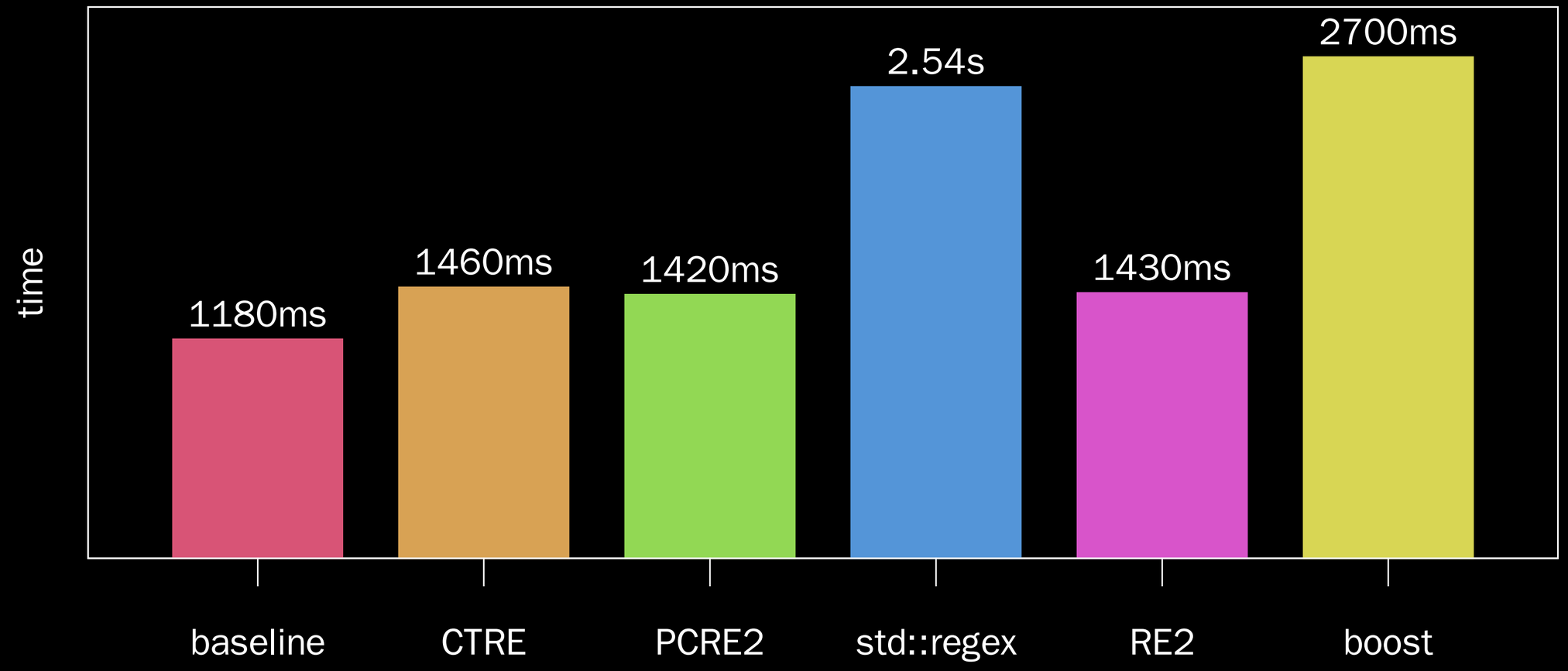
`clang -c -O0`



(less is better)

Compile Time of The Benchmark code.

`gcc -c -O0`



(less is better)

What's the behaviour of the library?

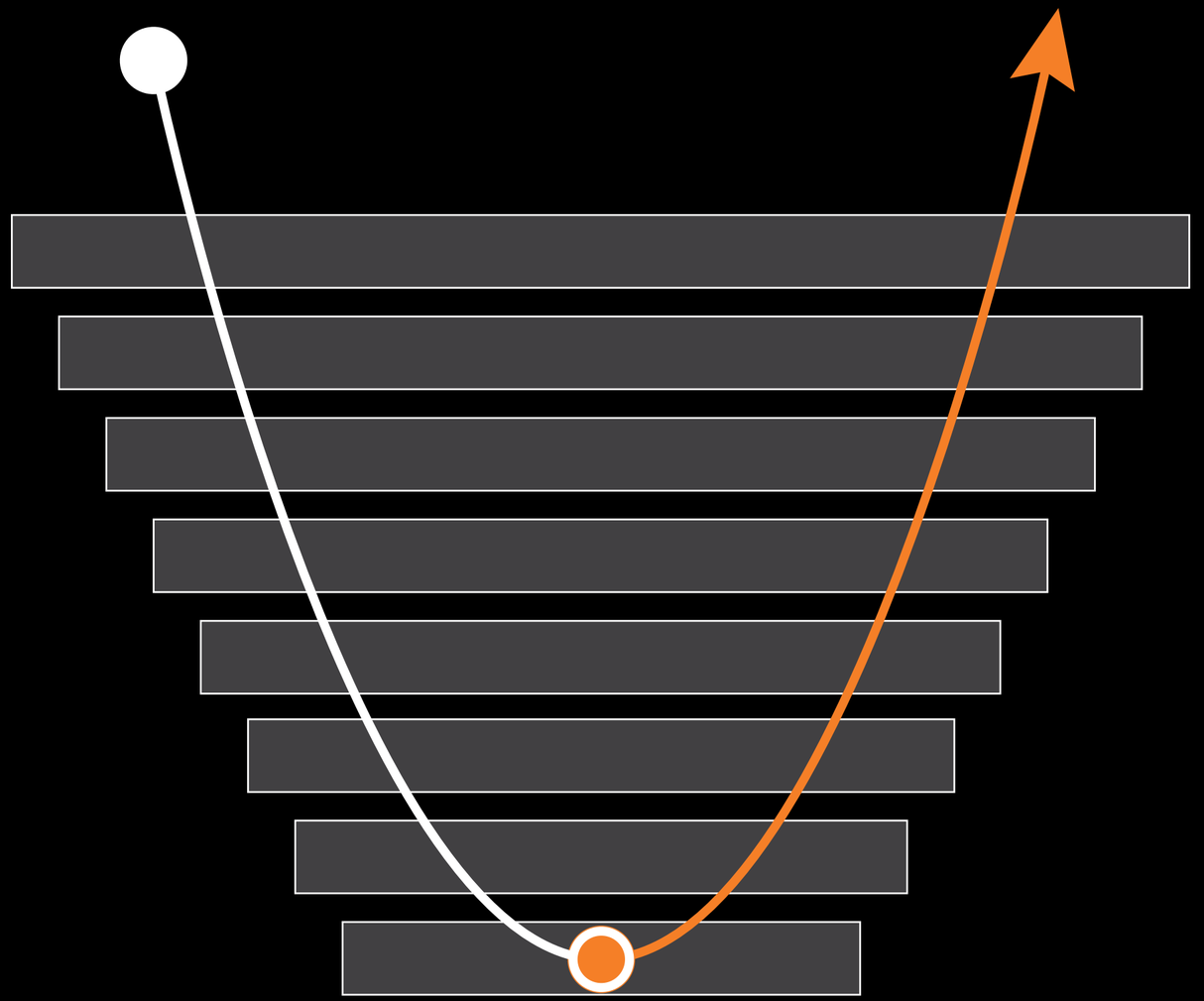
- Multiple different REs cost ~200ms each.
- Repeating the same REs cost virtually nothing (due to caching).
- Cost of one RE parsing is linear with its complexity.

What did we learn?

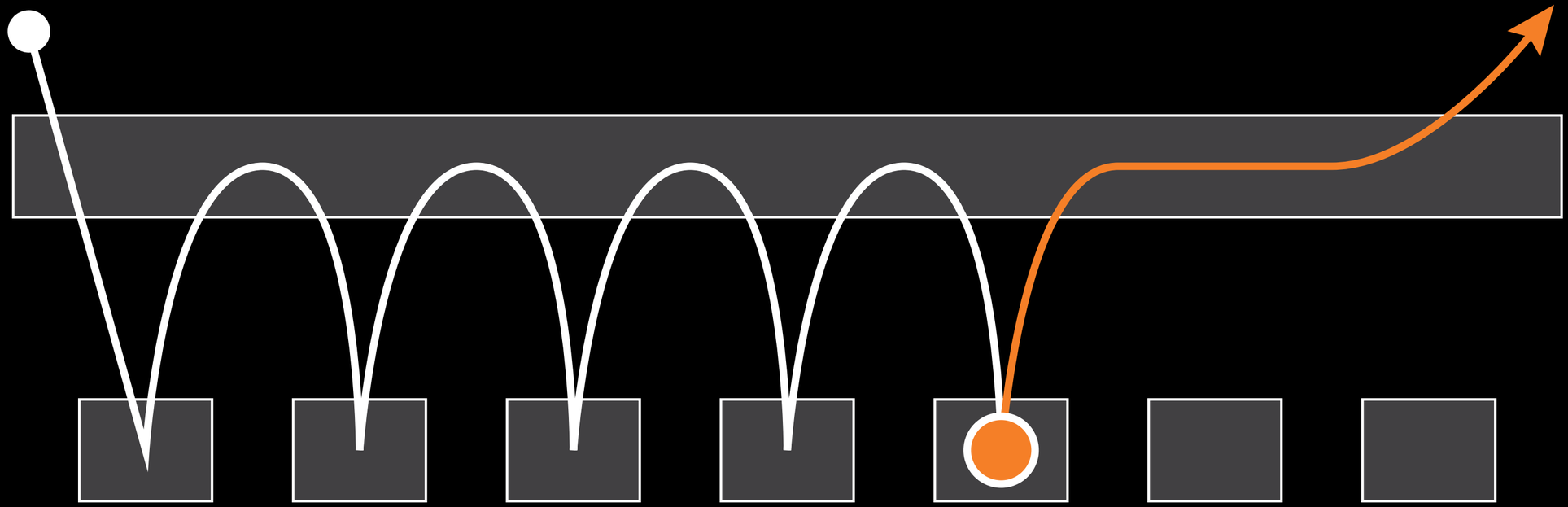
- Recursion and function overloading resolution are powerful tools.
- Pure functional programming keeps your code simple.
- Trust your compiler (but check its output).
- Type-list is the most useful compile-time data structure.

One more thing...

1024



But there is a no cycle usable with type-list!



- divide algorithm into pieces char by char
- store & restore state of parser

Store the parser state

```
enum class decision {
  undecided,
  correct,
  wrong
};

// move to next character
template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(pop_input, Stack stack, T subject) {
  // return parse<Pos+1>(stack, subject);
  return state<Pos+1, Stack, T, decision::undecided>();
}
```

Accept and Reject

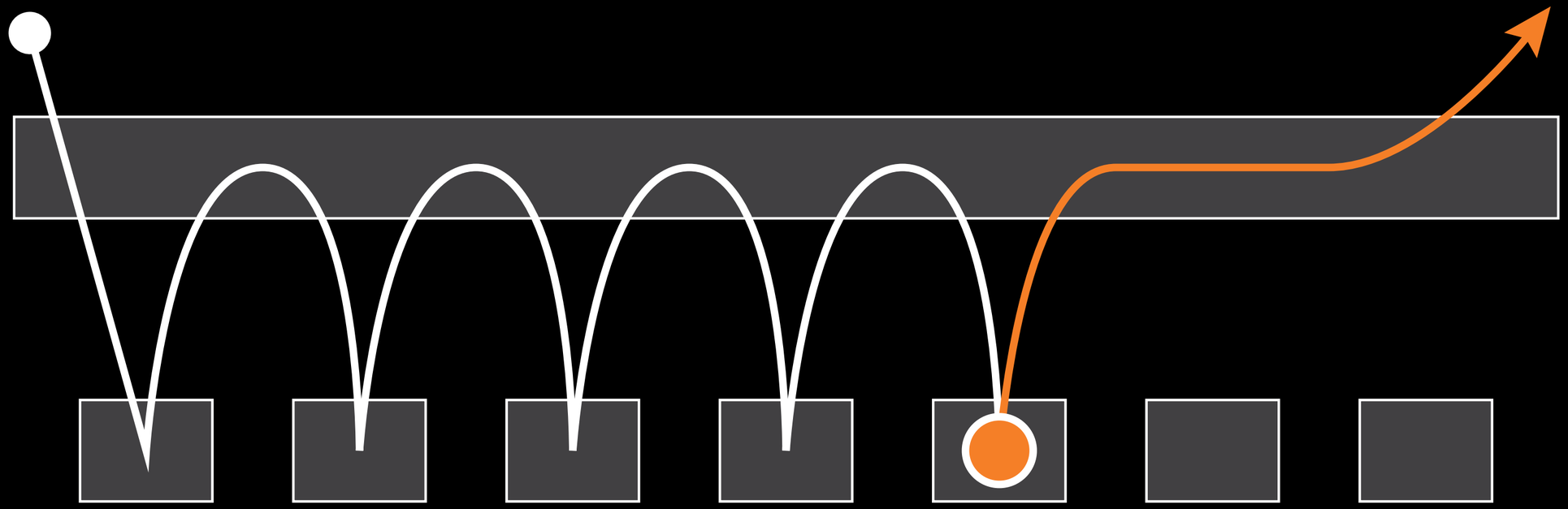
```
// instead of returning pair with subject and boolean flag

template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(reject, Stack s, T subject) {
  return state<Pos, Stack, T, decision::correct>();
}

template <size_t Pos, typename Stack, typename T>
 static constexpr auto move(accept, Stack s, T subject) {
  return state<Pos, Stack, T, decision::wrong>();
}
```

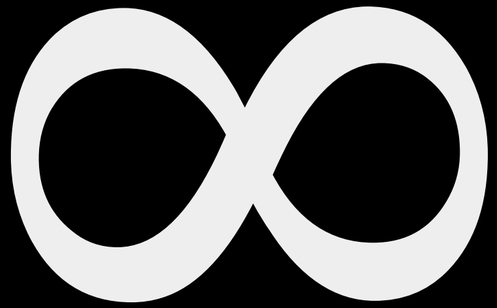
Restore the parser state

```
struct placeholder {};

template <size_t Pos, typename Stack, typename Subject, decision Decision>
 struct state {
  auto operator+(placeholder) {
    if (Decision == decision::undecided) {
      return parse<Pos>(Stack(), Subject());
    } else {
      return *this;
    }
  }
}
```

How to make it work?

```
template <size_t Idx> using index_placeholder = placeholder;

template <typename Subject> auto tr_parse(Subject s) {
  return tr_parse(s, std::make_index_sequence<input.length()>());
}

template <typename Subject, size_t... Idx>
 auto tr_parse(Subject s, std::index_sequence<Idx...>) {
  return pair(parse<0>(s) + ... + index_placeholder<Idx>());
}
```





Thank You!

You can find the slides and sources at:
compile-time.re