CS 1
Introduction to Computer Programming

Lecture 22: November 25, 2015

Regular Expressions

th.*g

^th.*g$

th?nksg.*g

th[an]{2}.*g

th[a-z]*g

th[^]*g

Previously

- Class inheritance
- Exceptions and classes
- C++, part 1

Today

- Regular expressions
  - (advanced string processing)

Fun quote

- From Jamie Zawinski
  - (programmer for the Netscape Navigator web browser, which later became Firefox)
- "Some people, when confronted with a problem, think *'I know, I'll use regular expressions.'* Now they have two problems."

What are regular expressions?

- Regular expressions are a very powerful way of processing strings
  - classifying strings
  - searching for patterns in strings
  - replacing parts of strings that match patterns

Applications of regular expressions

- Regular expressions are *very* heavily used in practical applications, for instance
  - bioinformatics
  - web programming
  - "data crunching"
  - and anywhere else strings are used

Disclaimers

- I can't cover everything about regular expressions in one lecture
  - Entire books have been written about them!
- I will focus on the most general/useful aspects of regular expressions as found in Python
  - see Python docs for more complete information
- Regular expressions are *not* Python-specific!
  - almost every language has a regular expression library, some more powerful than others

Terminology

- Regular expressions are also known as
  - regexps
  - regexes
  - REs
- for short

Theory

- There is a very rich theory behind regular expressions
- Regular expressions are related to
  - deterministic finite automata (DFA)
  - nondetermistic finite automata (NFA)
- Caltech's CS 21 course covers these topics
- [You don't need to understand the theory to use regular expressions]
  - but it's really interesting, so take CS 21 anyway!

In Python

- Regular expressions in Python require that you import the `re` module
- We will go over the main functions in this module later

The RE "language"

- Regular expressions are basically a kind of "little language" or "embedded language" for describing strings that exists inside Python
- This notion of "languages inside languages" may seem odd, but there are many examples of it in common use today

The RE "language"

- Other little languages:
  - HTML language for describing web pages
  - XML language(s) for describing arbitrarily structured data
  - JSON language for describing key-value pairs
- Python modules exist for all of these little languages, so working with these languages in Python is pretty easy
- Today, we'll just talk about the RE language

Example 1

- We have a string representing a DNA sequence

```
s = 'AGGTTCGGAATGAGATCCTAAG...'
```

- We want to find if a particular subsequence is found in the string `s`
  - for instance, the sequence `'ATTGCC'`
- How do we solve this?

Example 1

- Several ways of doing this in Python
- You can write an explicit loop:

```
found = False
for i, e in enumerate(s):
    if s[i:i+6] == 'ATTGCC':
        found = True
        break
```

Example 1

- Several ways of doing this in Python
- You can use the `in` operator:

```
found = 'ATTGCC' in s
```

- ☺

Example 1

- Several ways of doing this in Python
- Or you can use a *regular expression*:

```
import re  # regular expression module
match = re.search('ATTGCC', s)
if not match:
    found = False
else:
    found = True
```

- (What `match` is will be explained shortly)

Example 1

- In this case, the regular expression is just the string to be matched (`'ATTGCC'`)
- Using a regular expression here is no better than using the `in` operator
- However, if we make the problem a bit harder, we will see that regular expressions are much more convenient

Example 2

- New problem:
- Have an input DNA string, and want to look for substrings with this form:
  - A or T, A or T, A or T, G or C, G or C, G or C
  - *e.g.* ATTGCC, AAAGGG, ATACCG, etc.
- We can't use the `in` operator anymore!
  - At least, not without generating all of the $2^6 = 64$ possible substrings of that form
  - And even then it would be very inefficient

Example 2

- Let's try it with an explicit loop:

```
found = False
for i, e in enumerate(s):
    sub = s[i:i+6]
    if sub[0] in 'AT' \
       and sub[1] in 'AT' \
       and sub[2] in 'AT' \
       and sub[3] in 'CG' \
       and sub[4] in 'CG' \
       and sub[5] in 'CG':
       found = True
       break
```

Example 2

- Wow, was that ever tedious!
- How would you solve this with regular expressions?

```
import re
if not re.search('[AT][AT][AT][CG][CG][CG]', s):
    found = False
else:
    found = True
```

Example 2

- We can do even better than this:

```
import re
if not re.search('[AT]{3}[CG]{3}', s):
    found = False
else:
    found = True
```

- Moral: regular expressions can *drastically* simplify many string processing tasks

Note on style

- This code looks a bit ugly:

```
if not re.search('[AT]{3}[CG]{3}', s):
    found = False
else:
    found = True
```

- Why not just write this:

```
found = re.search('[AT]{3}[CG]{3}', s)
```

- Actually, you can, but **`re.search`** doesn't return a boolean, and you can do more with its return value (coming up)

The regular expression "language"

- We've seen several things that we've called "regular expressions":
  - `'ATTGCC'`
  - `'[AT][AT][AT][GC][GC][GC]'`
  - `'[AT]{3}[GC]{3}'`
- But what *are* regular expressions anyway?
- In Python, they are represented in two different ways

The regular expression "language"

1. Regular expressions are ordinary strings with a particular syntax
   - used by regular expression functions that expect these kinds of strings
2. Regular expressions are Python objects made from these strings

- For now, we'll stick to the first form of regexps, and discuss the other later

The regular expression "language"

- A regular expression string is a string which represents a *set of matching strings*
- Idea: you can *match* the regular expression against any of the set of matching strings, but not against any non-matching string
- To understand this, we need to know the syntax of regular expression strings

Raw strings

- Normal Python strings have special characters encoded using backslash *escape sequences*
  - `\n` = newline, `\t` = tab, etc.
- This will make our lives difficult when writing regexp strings, because regexps assign their own meanings to characters
- To get around this, Python provides a variant of strings called a "raw string" which have no escape sequences

Raw strings

- A Python string preceded immediately by the letter `r` is a "raw string"
- A raw string is a string which consists exactly of all the characters in the string, with (almost) no escape sequences
- `'foo\nbar\n'` is a regular Python string
- `r'foo\nbar\n'` is a raw string
  - the `'\n'` part in the raw string is *not* a newline character, but just a two-character sequence (the `\` character followed by the `n` character)

Raw strings

```
>>> print 'foo\nbar\n'
foo
bar

>>> print r'foo\nbar\n'
foo\nbar\n
```

Raw strings

- All regexps we describe will use raw strings to avoid problems
- In this lecture, when I write a string, I mean a raw string, so you should add the `r` prefix if you test the code out yourself
- Often, in practice, it doesn't matter, so in those cases you can use whatever you prefer (raw strings or regular Python strings)

Raw strings

- NOTE: Raw strings are *not* a special Python datatype!
- They are still just ordinary strings as far as Python is concerned
- The only difference is that the literal form of raw strings is different (*i.e.* you write the string in a different way)
- Similar to the situation with triple-quoted strings, docstrings, *etc.*

Regular expression syntax

- Regular expression strings assign new meanings to some of the characters in the string
- For instance, the characters:
  - `. * + ? ^ $ [ ] | ( ) { }`
  - all have special meanings inside regular expressions

Syntax: simple strings

- A string of non-special characters will match itself only
- Example: regexp string `'foo'` will match the string `'foo'` and nothing else
- If you want to match a string containing some of the special characters, you put a backslash (`\`) before the character
- Example: regexp string `'foo\?'` matches the string `'foo?'`

Syntax: the * character

- The `*` character means "zero or more of the preceding character"
  - actually it's more general than that, as we'll see shortly
- So the regexp `'a*'` matches
  - `''` (empty string)
  - `'a'`
  - `'aa'`
  - `'aaa'`
  - etc.

Syntax: the * character

- We can incorporate the `*` character into other regexps
- The regexp `'fo*ba*r'` matches
  - `'fbr'`
  - `'fbar'`
  - `'foooooobr'`
  - `'foobaaaaaaaar'`
  - etc.

Syntax: the + character

- The `+` character means "*one* or more of the preceding character"
- So the regexp `'fo+ba+r'` matches
  - `'fobar'`
  - `'fooooobaar'`
  - `'foobaaaaaaar'`
  - etc.
- but not
  - `'fbr'`

Syntax: the ? character

- The `?` character means "*zero* or *one* of the preceding character"
- So the regexp `'fo?ba?r'` matches
  - `'fbr'`
  - `'fobr'`
  - `'fbar'`
  - `'fobar'`
  - and that's it!

Syntax: the . character

- The `.` character means "any character except a newline"
- So the regexp `'f.b.r'` matches
  - `'fabar'`
  - `'fzbqr'`
  - `'f@b r'`
  - etc.

Combining special characters

- We can combine `.` and `*` or `+` to get useful regexps:
  - `'Mon.*on'` matches `'Monty Python'` and also `'Montreal Marathon'`
  - `'Par.+t'` matches `'Parrot'` and also `'Parrots are good to eat'`

Syntax: the ( ) characters

- The `(` and `)` characters (parentheses) define a *group*
- A group is a sequence of characters that can be acted on as a whole by a special character
- For instance: `'(foo)+bar'` matches
  - `'foobar'`
  - `'foofoobar'`
  - `'foofoofoobar'`
  - etc. (`+` special character acts on the entire substring `foo`, not just on one character)

Syntax: the ( ) characters

- What the `*`, `+`, `?` etc. characters act on can be either
  - a single character
  - a group of characters surrounded by parentheses
- We will refer to these as a *pattern* from now on
  - So the `*`, `+`, `?` characters act on the pattern that immediately precedes it

Syntax: the { } characters

- The `{` and `}` characters (curly braces) represent a number of repetitions
- `{n}`: previous pattern is repeated `n` times
- `{m, n}`: previous pattern is repeated between `m` and `n` times (at least `m`, at most `n`)
- where `m` and `n` are positive integers, `m <= n`

Syntax: the { } characters

- Example: `'(foo){2}'` matches `'foofoo'` but not `'foo'` or `'foofoofoo'`
- Example: `'ab{3,5}c'` matches `'abbbc'`, `'abbbbc'`, `'abbbbbc'`

Syntax: the [ ] characters

- The `[` and `]` characters (square brackets) represent a *set of characters* that can exist in the string being matched
- The set matches if *any* of the characters in the set is present at that location in the string
- Inside the `[` and `]` characters there are some extra abbreviations
  - I never said this wasn't complicated! ☹

Syntax: the [ ] characters

- Example: the regexp `'[aeiou]'` matches any of the letters `a`, `e`, `i`, `o`, `u`
- Example: the regexp `'[ACGT]+'` matches any DNA string made of the letters `A`, `C`, `G`, or `T` in any order, with at least one character in the string

Syntax: the [ ] characters

- Shortcut 1: inside `[` and `]` you can represent character ranges in order using the `-` character
- `[A-Z]` = `[ABC...Z]`
- `[A-Za-z]` = `[ABC...Zabc...z]`
- `[0-9]` = `[012...9]`
- Can only do this in ascending order
- Can't do *e.g.* `[z-a]` to get `[zyx...a]`
  - (would mean the same thing as `[a-z]` anyway)

Syntax: the [ ] characters

- Shortcut 2: inside `[` and `]`, if the first character is the `^` character, then match any character *except* for the characters inside the square brackets
- `[^a]` = any character except `a`
- `[^0-9]` = any character except a digit

Syntax: the | character

- The `|` (vertical bar) character represents alternatives; the regexp can match strings with *either* the pattern on the left *or* the pattern on the right of the `|` character
- Example: `'(foo)|(bar)'` will match either `'foo'` or `'bar'`
- Example `'(a+b)|(b+a)'` will match `'aaaab'`, `'bbbba'`, etc.

Syntax: the rest

- There are many more details and shortcuts in Python's regular expression syntax
- See the Python documentation for full details
- This will be enough for our purposes today

The `re` module

- Python's `re` module contains a number of functions for working with regular expressions
- We will discuss three of the most useful ones:
  - `re.match()`
  - `re.search()`
  - `re.sub()`
- but there are many more! (See the docs!)

`re.match()`

- The **`re.match()`** function takes two arguments:
  - a regexp, represented as a string
  - a string to match against
- and returns a "match object" if the string matches the regexp, or **`None`** if it doesn't
- The entire string doesn't have to match the regexp; only the *beginning* of the string needs to match for a match object to be returned

re.match()

- Examples:

```
>>> re.match('foo', 'foobar')
<_sre.SRE_Match object at 0x5adde8>
>>> re.match('foo', 'xxxxx')
```

[None]

```
>>> re.match('foo', 'afoo')
```

[None]

- We will see what we can do with match objects shortly

re.match()

- Note that `None` is considered to be `False` when used in an `if` statement, so we can do this:

```
if not re.match('foo', 'xxxxx'):
    found = False
else:
    found = True
```

- or just use `re.match(...)` as a boolean value itself:

```
found = re.match('foo', 'xxxxx')
```

re.match()

- More examples:

```
>>> re.match('a+b', 'aaaabbbbcccc')
<_sre.SRE_Match object at 0x5adde8>
>>> re.match('a+b', 'baaaabbbbccc')
```

[None]

- However, often we want to be able to look for a regexp located at some unknown place *inside* a string, which leads us to...

`re.search()`

- **`re.search()`** is like **`re.match()`**, but it will return a match object if the regexp matches the string at *any* location in the string (not just starting at the beginning)
- If there are multiple matches, the first one is the one that's returned

re.search()

- Examples:

```
>>> re.search('foo', 'afoo')
<_sre.SRE_Match object at 0x5ade20>
>>> re.search('foo', 'xxx')
```

[None]

```
>>> re.search('[AT]+', 'GGGCCAATTAACCC')
<_sre.SRE_Match object at 0x5ade20>
```

Match objects

- When a regular expression matches a string in functions like `re.match()`, `re.search()`, the function returns a match object
- These objects have several useful methods that give information about the match:
  - `start()`, `end()`, `span()`
  - `group()`
  - `groups()`

Match objects

- `start()`: returns the index of the first character matched
- `end()`: returns the index of one past the last character in the string
- `span()`: returns a tuple of (`start()`, `end()`)
- `group(n)`: returns the contents of the n^{th} group *i.e.* the part of the string that matched the n^{th} parenthesized part of the regexp
  - (group 0 is the entire match)
- `groups()`: returns the contents of all groups (except for group 0)

Match objects

- Example:

```
>>> m = re.search('def', 'abcdefghi')
>>> m.start()
3
>>> m.end()
6
>>> m.span()
(3, 6)
```

Match objects

- Example:

```
>>> m = re.match('([0-9]{3})-([0-9]{4})',
  '555-0101')
>>> m.groups()
('555', '0101')
>>> m.group(0)
'555-0101'   # entire match
>>> m.group(1)
'555'
>>> m.group(2)
'0101'
```

Greed

- We say that regexp special characters like * and + are *greedy*
- They match as many characters/patterns as they possibly can
- This is important when searching for a regexp match in a larger string

Greed

- Example: we want to match the string `'Parrots are neat!'` using the regexp `'Par.*t'`
- There are two possible matches starting from the beginning of the string:
  - `'Parrot'`
  - `'Parrots are neat'`
- Which one should Python choose?

Greed

- In Python:

```
>>> s = 'Parrots are neat!'
>>> m = re.match('Par.*t', s)
>>> m.group(0)
'Parrots are neat'
```

- Python's regular expressions are *greedy*
- They match as much of the string as they possibly can
- Can cause problems if you're not aware of it!

Overcoming greed

- There are also *non-greedy* versions of some regexp operators:
  - `*?` is a non-greedy version of `*`
  - `+?` is a non-greedy version of `+`
- They look for the *shortest* match, not the longest

```
>>> s = 'Parrots are neat!'
>>> m = re.match('Par.*?t', s)
>>> m.group(0)
'Parrot'
```

Substitutions

- So far, we've seen how to match strings (or parts of strings) based on regexps
- Very often, you want to *find* a regexp and *substitute* something else for it
  - like the find/replace feature of editors
- With regexps, we use the **`re.sub()`** function to do this

Substitutions

- `re.sub()` takes
  - a regexp
  - the string the regexp matches will be replaced with
  - the string to be substituted into
- and returns a new string, which includes the substitutions (substitutes *all* matches)
- Example:

```
>>> re.sub('MIT', 'Caltech',
      'MIT is the best school.')
Caltech is the best school.
```

Substitutions

- `re.sub()`'s second argument (the replacement string) can also refer to groups matched in the first argument (the regexp)
- Notation: `\1` is the first group matched, `\2` is the second group, etc.
- Example: switching first and last names

```
>>> re.sub('([A-Za-z]+) ([A-Za-z]+)',
  r'\2, \1', 'Joe Blow')
Blow, Joe
```

Substitutions

- Example: switching first and last names

```
>>> re.sub('([A-Za-z]+) ([A-Za-z]+)',
  r'\2, \1', 'Joe Blow')
Blow, Joe
```

- Note the raw string: `r'\2, \1'`; it's necessary!
  - otherwise it would have to be `'\\2, \\1'`
  - which is really tedious to write

Pattern objects

- We said before that Python regexps could be either strings or regexp objects
- We've worked with regexps as strings, but how do we create regexp objects?
- Answer: we use the `re.compile()` function
- This turns a regexp (represented as a string) into a regexp object
  - also known as a "pattern object"

Pattern objects

- Example:

```
>>> p = re.compile('[ATGC]+')
```

- Now `p` is a pattern object:

```
>>> p
<_sre.SRE_Pattern object at 0x548f70>
```

Pattern objects

- You can use the pattern object to do matching, searching, and substituting using methods on the pattern object:

```
>>> m = p.match('AGGCCTTxxx')
>>> m.span()
(0, 7)
>>> m = p.search('xxxxAGCCGGTxxxx')
>>> m.span()
(4, 11)
```

Pattern objects

- You can use the pattern object to do matching, searching, and substituting using methods on the pattern object:

```
>>> p.sub('', 'xxxxAGCCGGTyyyy')
xxxxyyyy
```

- This deletes the pattern from the string

Pattern objects

- Pattern objects don't let you do anything you couldn't do without them
- However, they are more efficient than using strings as regexps
  - Python can pre-process the regexp so that the regexp functions work more efficiently
- If you're using the same regexp over and over, you should probably `compile()` it into a pattern object

Final example

- We'll work through a more realistic example to see what real regexps are like
- We want to write a regexp that can match floating-point numbers with these properties:
  - optional minus sign at the beginning
  - decimal point is required
  - must have at least one digit before the decimal place
  - can have zero or more digits after the decimal place
  - optionally can have an exponent using e or E followed by the exponent (positive or negative)

Final example

- We will use groups to pick out
  - the minus sign (if any)
  - the part before the decimal point
  - the part after the decimal point (if any)
  - the exponent (if any)
- We will compile our regexp using `re.compile()` and use the `groups()` method on match objects to show the groups we matched

Floating-point number regexp

- The minus sign is optional, and will be a group
- The regexp we need for this is `'(-?)'`
- The digits before the decimal point are *not* optional
  - must have at least one digit
  - must be followed by a literal `.` character
  - these digits form a group, but the `.` is not part of the group
- You might think that the regexp for this part should be `'([0-9]+).'` – or is it?

Floating-point number regexp

- You might think that the regexp for this part should be `'([0-9]+).'` – or is it?
- Recall: the `.` character matches any character except a newline
- For a literal `.` character, we have to "escape" it by preceding it with a backslash (`\.`)
- So the regexp for this part is `'([0-9]+)\.'`

Floating-point number regexp

- The part after the decimal place (but before the exponent) is zero or more digits
- It will also be a group
- This is easy to write as a regexp: `([0-9]*)`

Floating-point number regexp

- The exponent has three components:
  - the letter e or E
  - an optional sign (+ or -)
  - one or more digits
- of which the last two need to be in a group
- And: the entire exponent is optional!
- This requires a fairly complicated regexp:

```
([eE]([+-]?[0-9]+))?
```

Floating-point number regexp

- Putting all of it together, we have:

```
'(-?)([0-9]+)\.([0-9]*)([eE]([+-]?[0-9]+))?'
```

- We should make it a raw string, just to be on the safe side:

```
r'(-?)([0-9]+)\.([0-9]*)([eE]([+-]?[0-9]+))?'
```

- We should compile it to make it into a regexp object (for efficiency):

```
>>> f = re.compile(r'(-?)([0-9]+)\.([0-9]*)([eE]
  ([+-]?[0-9]+))?')
```

Floating-point number regexp

- Let's test our shiny new regexp!

```
>>> f.match('1001.0').groups()
('', '1001', '0', None, None)
```

- No sign, `'1001'` before the decimal point, `'0'` after, no exponent

```
>>> f.match('-1001.0e-10')
('-', '1001', '0', 'e-10', '-10')
```

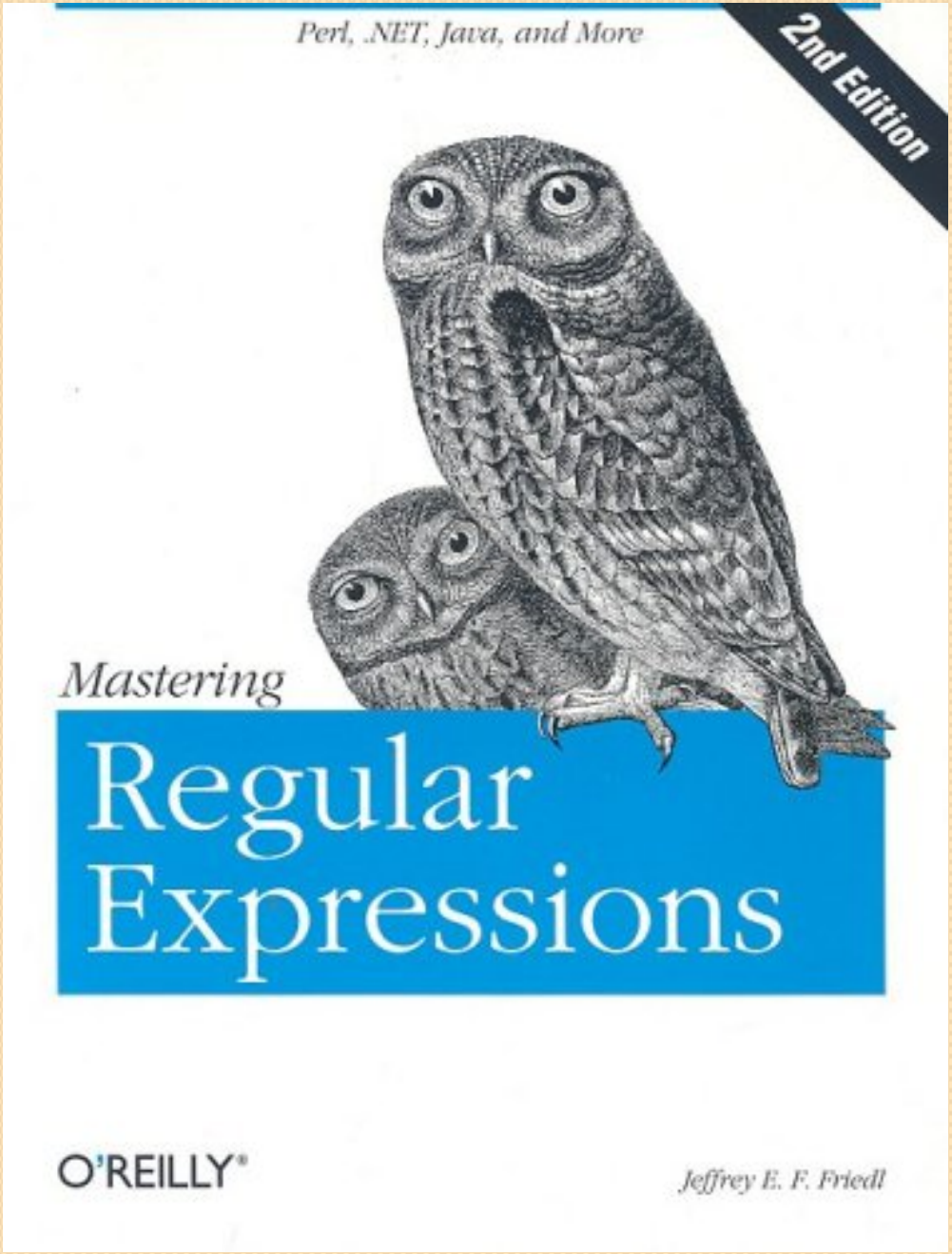
- A minus sign, `'1001'` before the decimal point, `'0'` after, and `'-10'` as the exponent
- It works! ☺

Summing up

- Regular expressions are complicated, and will take a while to get comfortable with
- However, they are also one of the most useful tools in a programmer's toolkit
- If you do a lot of string processing, you will use regular expressions more than you can probably believe at this point
- Whatever effort you put into learning them will be very richly rewarded

For reference

- The Python documentation:
  - `http://docs.python.org/library/re.html`
- Book: Mastering Regular Expressions by Jeffrey Friedl (O'Reilly and Associates)
  - the most definitive resource I know on regexps
  - (544 pages!)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