

Looping and
iteration

Dr. Giuseppe
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Introduction

Repeated
behaviors

Repeating
behaviors in
Python

Reasoning
about `while`

Termination
(or lack
thereof)

Exponential
explosion of
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Looping and iteration

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Lecture topics

- Repeated behaviors
- `while` statements and their semantics
- Expressive power of `while`
- Termination and infinite iteration
- Explosion of states with `while`

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Repeated behaviors

- Sometimes running code just once is not enough
- We can *loop* execution of a block of code until some *condition* is met
- Extreme increase in expressive power

Repeated behaviors

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Repeated behaviors

- *While there are hostile aliens*
- *Do attack an alien*

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Repeated behaviors

- Loops can solve very big problems
- Each step of the loop removes a part of the problem
- We typically stop when all parts of the problem have been removed

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Breaking problems up

- Problem: **kill all aliens**
- Problem piece: **a single alien to be killed**
- Solution piece: **attack a single alien**
- Termination condition: **there are no more aliens**

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Breaking problems up

- Of course loops can be combined with each other
- This means that we can *cascade* repetition
- This is the building block of *intelligent decisions* in our programs

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Breaking problems up

- *While there are hostile alien armies*
 - *Do pick an alien army*
 - *While there are aliens in the army*
 - *Do attack an alien*

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`while`

- Python offers built-in facilities for repetition
- `while` statement
- We can repeat execution of a block of code

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while

- The general form is `while CONDITION: BODY` (w_{CB})
- If the condition is true, then we jump to the beginning of BODY, otherwise we jump to the end of the whole while

$$\left\{ \begin{array}{ll} (PC, S) \xrightarrow{w_{CB}} (firstLine(B), S) & \text{when } (PC, S) \xrightarrow{C} TRUE \\ (PC, S) \xrightarrow{w_{CB}} (skipAfter(B), S) & \text{when } (PC, S) \xrightarrow{C} FALSE \end{array} \right.$$

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`while`

- Remember that Python is *indentation*-based
- White-spaces go at the beginning of some lines
- A more indented line is *within* a less indented line above

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`while`

- Indentation specifies where the body begins and ends
- The general form of a `while` is thus:
 - `while COND:`
 - `newline`
 - **indentation**
 - `code of body`
 - **de-indentation**

A correct example

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```
n = 64
i = 0
while n > 1:
    n = n / 2
    i = i + 1
```

An incorrect example

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```
n = 64
i = 0
while n > 1:
    n = n / 2
    i = i + 1
```

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while

- while statements eventually terminate (hopefully)
- if the condition evaluates to False, then we skip after the end of the while

After a while

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```
n = 64
i = 0
while n > 1:
    n = n / 2
    i = i + 1
print(i)
```


After a while?

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Without indentation, this:

```
n = 64
i = 0
while n > 1:
n = n / 2
i = i + 1
print(i)
```

would be indistinguishable from both:

<pre>n = 64 i = 0 while n > 1: n = n / 2 i = i + 1 print(i)</pre>	<pre>n = 64 i = 0 while n > 1: n = n / 2 i = i + 1 print(i)</pre>
--	--

Reasoning about while

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`while`

- `while` effectively rewrites the code to become as long as the problem needs
- Until run-time, we are not really sure how long the code will become

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What values of n will we print?

```
i = 0
j = 1
n = 0
while i < 10:
    i = i + 1
    n = n + j
    print(n),
```

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What values of `n` will we print?

```
i = 0
j = 1
n = 0
while i < 10:
    i = i + 1
    n = n + j
    print(n),
```

1 2 3 4 5 6 7 8 9 10

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What values of `n` will we print?

```
i = 0
j = 2
n = 0
while i < 10:
    i = i + 1
    n = n + j
    print(n),
```

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What values of n will we print?

```
i = 0
j = 2
n = 0
while i < 10:
    i = i + 1
    n = n + j
    print(n),
```

2 4 6 8 10 12 14 16 18 20

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while

- Each iteration produces new values of the variables
- These new values are then fed back into the next iteration
- Eventually these cause the condition to become false
 - Or the program runs forever and never produces a result

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while

- Each iteration produces new values of the variables
- These new values are then fed back into the next iteration
- Eventually these cause the condition to become false
 - Or the program runs forever and never produces a result
 - We'd rather not have this one

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i	j	n
0	2	0

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

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i	j	n
0	2	0

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

i	j	n
1	2	2

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i	j	n
1	2	2

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

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i	j	n
1	2	2

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

i	j	n
2	2	4

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i	j	n
2	2	4

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

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i	j	n
2	2	4

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

i	j	n
3	2	6

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After k iterations (for $k < 10$):

i	j	n
k	2	$2 * k$

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

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After k iterations (for $k < 10$):

i	j	n
k	2	$2 * k$

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

i	j	n
$k+1$	2	$2 * k + 2$

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After k iterations (for $k = 10$):

i	j	n
10	2	20

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

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After k iterations (for $k = 10$):

i	j	n
10	2	20

```
while i < 10:  
    i = i + 1  
    n = n + j  
    print(n),
```

We jump to the first instruction **after** the while loop, and do not touch the state further.

i	j	n
10	2	20

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Readability and termination

- The loop above is *well designed*
- All iterations produce a new piece of a logical series
 - (The j -th row of the table of multiplication)

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Readability and termination

- After each iteration we know that we have i elements correctly computed
- After each iteration we know that we have $10-i$ elements still to compute
- When $i=10$ then we have $10-10$ elements still to compute
 - This is the **termination condition**
 - Since i keeps growing, we know that eventually the termination condition will be met

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Nesting

- Loops can be nested
- A loop can be inside a loop (which can further be inside other loops)
- This makes it slightly harder to reason

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```
j = 1
while j <= 10:
    i = 0
    n = 0
    while i < 10:
        i = i + 1
        n = n + j
        print(n),
        print("\t"),
    j = j + 1
    print("")
```

Example nested while's

We now know that the semantics of the inner loop is **print the j -th row of the table of multiplication**, so instead of reasoning on:

```
j = 1
while j <= 10:
    i = 0
    n = 0
    while i < 10:
        i = i + 1
        n = n + j
        print(n),
        print("\t"),
    j = j + 1
    print("")
```

we reason on:

```
j = 1
while j <= 10:
    print the  $j$ -th row of the table of multiplication
    j = j + 1
    print("")
```

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j	output
1	nothing

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```


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j	output
1	nothing

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```

j	output
2	1st row of table

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j	output
2	1st row of table

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```

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j	output
2	1st row of table

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```

j	output
3	1st and 2nd rows of table

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Thus for all k 's such that $k \leq 10$:

j	output
k	first $k-1$ rows of table

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```

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Thus for all k 's such that $k \leq 10$:

j	output
k	first $k-1$ rows of table

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")
```

j	output
k+1	first k rows of table

Example nested while's

Eventually we get $j = 11$:

j	output	PC
11	first 10 rows of table	1

```
while j <= 10:  
    print the j-th row of the table of multiplication  
    j = j + 1  
    print("")  
...
```

1
2
3
4
5

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Eventually we get $j = 11$:

j	output	PC
11	first 10 rows of table	1

```
while j <= 10:
    print the j-th row of the table of multiplication
    j = j + 1
    print("")
...
```

j	output	PC
11	first 10 rows of table	5

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Wait! It gets worse!

- It is not guaranteed that a loop will terminate
- A loop that does not terminate gets the program stuck forever
- It is a bit sad for the machine
- Care when designing loops is needed to prevent this

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Care in the design

- A loop changes the state of the program many times
- A **good** loop changes the state in one **direction**
- Every step should bring us closer to the **final state**
- The condition defines the aspects of the final state

Example non terminating while

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```
i = 1
while i > 0:
    i = i + 1
    print(i)
```

What is the issue here?

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```
i = 1
while i > 0:
    i = i + 1
    print(i)
```

What is the issue here?

Iterations do not go **towards** the condition, but **away** from it.

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This is not a duplicated slide.

```
i = 1
while i < 10:
    i = i + 1
    print(i)
```

What is the issue here?

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This is not a duplicated slide.

```
i = 1
while i < 10:
    i = i + 1
    print(i)
```

What is the issue here?

Iterations are **orthogonal (unrelated)** to the condition.

No iteration changes elements tested in the condition.

Exponential explosion of potential control-paths

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Exponential explosion of potential control-paths

- How many things can happen in a `while` loop?
- Depends on its content

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Exponential explosion of potential control-paths

- The more we nest loops and conditionals within a loop...

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Exponential explosion of potential control-paths

- The more we nest loops and conditionals within a loop...
- ...the more things may happen at run-time

Loops with nested if's

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```
while C0:  
    if C1:  
        A1  
    else:  
        B1
```

How many execution paths per **N** iterations of the loop?

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```
while C0:  
    if C1:  
        A1  
    else:  
        B1
```

How many execution paths per **N** iterations of the loop?

2 execution paths per iteration

2^N execution paths per N iterations

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```
while C0:  
    if C1:  
        A1  
    else:  
        B1
```

Example: execution paths per **3** iterations of the loop.

A1 A1 A1

A1 A1 B1

A1 B1 A1

A1 B1 B1

B1 A1 A1

B1 A1 B1

B1 B1 A1

B1 B1 B1

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Exponential explosion of potential control-paths

- Consider a loop that performs m iterations
- With n if's inside
- Each iteration can have 2^n possible execution paths
- The whole loop can have $2^{n \times m}$ possible execution paths^a

$$^a 2^{2 \times 10} = 1048576$$

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Exponential explosion of potential control-paths

- Each path can alter the state in a different way
- After a `while` with many billions possible paths
 - We have many billions possible resulting states

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Exponential explosion of potential control-paths

- The more nested the code inside a `while`
- The more complex its behavior
- *The harder it is to reason about it!*

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The value of reasoning

- **Always keep in mind:**
- You have the power to make your own life a living Hell...

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The value of reasoning

- **Always keep in mind:**
- You have the power to make your own life a living Hell...
- ...unless you reason first and then structure code logically

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The best of luck, and thanks for the
attention!