Lecture #18: Complexity, Memoization
How Fast Is This (I)?

• For this program:

```python
for x in range(N):
    if L[x] < 0:
        c += 1
```

• What is the worst-case time, measured in number of comparisons?

• What is the worst-case time, measured in number of additions (+=)?

• How about here?

```python
for x in range(N):
    if L[x] < 0:
        c += 1
        break
```
How Fast Is This (I)?

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```

# Answer: $\Theta(N)$ comparisons

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• What is the worst-case time, measured in number of additions ($+=\$)?

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# Answer: \( \Theta(N) \) additions

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How Fast Is This (I)?

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  ```python
  for x in range(N):
      if L[x] < 0:
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  # Answer: \( \Theta(N) \) comparisons
  # Answer: \( \Theta(N) \) additions
  ```

- What is the worst-case time, measured in number of comparisons?
- What is the worst-case time, measured in number of additions (+=)?
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  for x in range(N):
      if L[x] < 0:
          c += 1
          break
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# Answer: $\Theta(N)$ additions

• What is the worst-case time, measured in number of comparisons?

• What is the worst-case time, measured in number of additions (+=)?

• How about here?

```python
for x in range(N):
    if L[x] < 0:
        c += 1
        break
```

# Answer: $\Theta(N)$ comparisons

# Answer: $\Theta(1)$ additions
How Fast Is This (II)?

• Assume that execution of \( f \) takes constant time.

• What is the complexity of this program, measured by number of calls to \( f \)? (Simplest answer)

```python
for x in range(2*N):
    f(x, x, x)
    for y in range(3*N):
        f(x, y, y)
        for z in range(4*N):
            f(x, y, z)
```
How Fast Is This (II)?

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```

# Answer: $\Theta(N^3)$
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# Answer: $\Theta(N^3)$

• Why not $\Theta(24N^3 + 6N^2 + 2N)$?
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```

# Answer: \( \Theta(N^3) \)

• Why not \( \Theta(24N^3 + 6N^2 + 2N) \)? That's correct, but equivalent to the simpler answer of \( \Theta(N^3) \).
How Fast Is This (III)?

- What is the complexity of this program, measured by number of calls to $f$?

```python
for x in range(N):
    for y in range(x):
        f(x, y)
```
How Fast Is This (III)?

• What is the complexity of this program, measured by number of calls to \( f \)?

```python
for x in range(N):        # Answer \( \Theta(N^2) \)
    for y in range(x):
        f(x, y)
```

• This is an arithmetic series \( 0+1+2+\cdots+N−1 = \frac{N(N−1)}{2} \in \Theta(N^2). \)
How Fast Is This (IV)?

- What about this one, measured by number of calls to \( f \)?
- How about measured by number of comparisons (<)?

\[
\begin{align*}
z &= 0 \\
\text{for } x \text{ in range}(N): \\
& \quad \text{for } y \text{ in range}(N): \\
& \quad \quad \text{while } z < N: \\
& \quad \quad \quad f(x, y, z) \\
& \quad \quad z += 1
\end{align*}
\]
How Fast Is This (IV)?

- What about this one, measured by number of calls to \( f \)?
- How about measured by number of comparisons (<)?

\[
\begin{align*}
\text{z} &= 0 \\
\text{for } x \text{ in range}(N): & \quad \# \text{Answer } \Theta(N) \text{ calls to } f. \\
\text{for } y \text{ in range}(N): & \\
\text{while } z < N: & \\
\text{f}(x, y, z) & \\
\text{z} &= 1
\end{align*}
\]
How Fast Is This (IV)?

- What about this one, measured by number of calls to $f$?
- How about measured by number of comparisons ($<$)?

```python
z = 0
for x in range(N):
    for y in range(N):
        while z < N:
            f(x, y, z)
            z += 1
```

- In practice, which measure (calls to $f$ or comparisons) would matter?
How Fast Is This (IV)?

• What about this one, measured by number of calls to $f$?

• How about measured by number of comparisons ($<$)?

  $z = 0$
  for $x$ in range($N$):  # Answer $\Theta(N)$ calls to $f$
    for $y$ in range($N$):  # Answer $\Theta(N^2)$ comparisons.
      while $z < N$:
        $f(x, y, z)$
        $z += 1$

• In practice, which measure (calls to $f$ or comparisons) would matter?

• Depends on size of $N$, actual cost of $f$. For large enough $N$, comparisons will matter more.
Avoiding Redundant Computation

• Consider again the classic Fibonacci recursion:

```python
def fib(n):
    if n <= 1:
        return n
    else:
        return fib(n-1) + fib(n-2)
```

• This is tree recursion with a serious speed problem.

• Computation of, say `fib(5)` computes `fib(2)` several times, because both `fib(4)` and `fib(3)` compute it, and both `fib(5)` and `fib(4)` compute `fib(3)`. Computing time grows exponentially.

• The usual iterative version does not have this problem because it saves the results of the recursive calls (in effect) and reuses them.

```python
def fib(n):
    if n <= 1: return n
    a, b = 0, 1
    for k in range(2, n+1): a, b = b, a+b
    return b
```
Change Counting

- Consider the problem of determining the number of ways to give change for some amount of money:

```python
def count_change(amount, coins = (50, 25, 10, 5, 1)):
    """Return the number of ways to make change for AMOUNT, where the coin denominations are given by COINS."
    """
    if amount == 0:
        return 1
    elif len(coins) == 0 or amount < 0:
        return 0
    else:
        # = Ways with largest coin + Ways without largest coin
        return count_change(amount-coins[0], coins) + \
        count_change(amount, coins[1:])
```

- Here, we often revisit the same subproblem:
  - E.g., Consider making change for 87 cents.
  - When we choose to use one half-dollar piece, we have the same subproblem as when we choose to use no half-dollars and two quarters.
Memoizing

- Extending the iterative Fibonacci idea, let's keep around a table ("memo table") of previously computed values.
- Consult the table before using the full computation.
- Example: `count_change`:

  ```python
  def count_change(amount, coins = (50, 25, 10, 5, 1)):
      memo_table = {}
      def count_change(amount, coins):
          if (amount, coins) not in memo_table:
              memo_table[amount,coins] = full_count_change(amount, coins)
              return memo_table[amount,coins]
      def full_count_change(amount, coins):
          # original recursive solution goes here verbatim
          # when it calls count_change, calls memoized version.
          return count_change(amount,coins)
  ```

- Question: how could we test for infinite recursion?
Optimizing Memoization

• Used a dictionary to memoize count_change, which is highly general, but can be relatively slow.

• More often, we use arrays indexed by integers (lists in Python), but the idea is the same.

• For example, in the count_change program, we can index by amount and by the starting index of the original value of coins that we use.

```python
def count_change(amount, coins = (50, 25, 10, 5, 1)):
    # memo_table[amt][k] contains the value computed for
    #   count_change(amt, coins[k:])
    memo_table = [ [-1] * (len(coins)+1) for i in range(amount+1) ]

def count_change(amount, coins):
    if amount < 0: return 0
    elif memo_table[amount][len(coins)] == -1:  
        memo_table[amount][len(coins)]
            = full_count_change(amount, coins)
    return memo_table[amount][len(coins)]

...
Order of Calls

- Going one step further, we can analyze the order in which our program ends up filling in the table.

- So consider adding some tracing to our memoized `count_change` program:

```python
memo_table = {}
def count_change(amount, coins):
    ... full_count_change(amount, coins) ...
    return memo_table[amount,coins]
@trace
def full_count_change(amount, coins):
    if amount == 0: return 1
    elif len(coins) == 0 or amount < 0: return 0
    else:
        return count_change(amount, coins[1:]) \
        + count_change(amount-coins[0], coins)
return count_change(amount,coins)
```
Result of Tracing

- Consider `count_change(57)` (returns only):

  ```
  full_count_change(57, ()) -> 0  # Need shorter 'coins' arguments
  full_count_change(56, ()) -> 0  # first.
  ...
  full_count_change(1, ()) -> 0  # For same coins, need smaller
  full_count_change(0, (1,)) -> 1  # amounts first.
  full_count_change(1, (1,)) -> 1
  ...
  full_count_change(57, (1,)) -> 1
  full_count_change(2, (5, 1)) -> 1
  full_count_change(7, (5, 1)) -> 2
  ...
  full_count_change(57, (5, 1)) -> 12
  full_count_change(7, (10, 5, 1)) -> 2
  full_count_change(17, (10, 5, 1)) -> 6
  ...
  full_count_change(32, (10, 5, 1)) -> 16
  full_count_change(7, (25, 10, 5, 1)) -> 2
  full_count_change(32, (25, 10, 5, 1)) -> 18
  full_count_change(57, (25, 10, 5, 1)) -> 60
  full_count_change(7, (50, 25, 10, 5, 1)) -> 2
  full_count_change(57, (50, 25, 10, 5, 1)) -> 62
  ```
Dynamic Programming

- Now rewrite `count_change` to make the order of calls explicit, so that we needn’t check to see if a value is memoized.

- Technique is called *dynamic programming* (for some reason).

- We start with the base cases (0 coins) and work backwards.

```python
def count_change(amount, coins = (50, 25, 10, 5, 1)):
    memo_table = [ [-1] * (len(coins)+1) for i in range(amount+1) ]
def count_change(amount, coins):
    if amount < 0: return 0
    else: return memo_table[amount][len(coins)]
def full_count_change(amount, coins): # How often called?
    ... # (calls count_change for recursive results)
    for a in range(0, amount+1):
        memo_table[a][0] = full_count_change(a, ())
    for k in range(1, len(coins) + 1):
        for a in range(1, amount+1):
            memo_table[a][k] = full_count_change(a, coins[-k:])
    return count_change(amount, coins)
```