Principled Programming

Introduction to Coding in Any Imperative Language

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Cellular Automata

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Introduction

We illustrate two-dimensional arrays, and enumerations over them, using the examples of Cellular Automata and the Game of Life.

Cellular Automata model the Universe as a rectangular grid of *cells*, each in a given *state*. Time progresses in discrete steps. On each clock tick, each cell simultaneously decides what state to enter based on its current state and the current states of its neighbors. Each cell makes its decision independently, but all cells follow the same rules.

The Game of Life is a particular Cellular Automaton that models birth and death.

Systematic top-down development of an entire program is illustrated. Deeply-nested **for**-statements in the code arise naturally as a consequence of stepwise refinement, but are readily understood.

Class `Sim` models the notion of a Cellular Automaton, and its simulation.

```
class Sim:
    ____________
```

☞ **Aggregate the definitions of related variables and methods in a class.**

The simulation as a whole is implemented as method `main`.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        ___________
```

☞ **Aggregate the definitions of related variables and methods in a class.**

A *class method* is defined within a class using

- Decorator `@classmethod`
- First parameter **`cls`**

The simulation as a whole is implemented as method `main`.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        ___________
```

☞ **Aggregate the definitions of related variables and methods in a class.**

A *class method* is defined within a class using

- Decorator `@classmethod`
- First parameter **`cls`**

The simulation as a whole is implemented as method `main`.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        ___________
```

The simulation will be run by invoking this class method using its qualified name, i.e., `Sim.main()`, which passes the class itself as an implicit first argument matching **`cls`**.

☞ **Aggregate the definitions of related variables and methods in a class.**

The simulation as a whole is implemented as method `main`.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        __________
```

☞ **A method header-comment specifies the effect of invoking it, and (if the method has non-None type) the value returned. If the method has parameters, the specification is written in terms of those parameters.**

For the implementation of `main`, adopt the pattern that first initializes, then computes.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        #.Initialize.
        #.Compute.
```

☞ **Master stylized code patterns, and use them.**

Instantiate placeholders *Initialize* and *Compute* for the problem at hand.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        #.Create the initial Universe and display it.
        #.Simulate and display LAST_GEN additional generations.
```

☞ **Master stylized code patterns, and use them.**

Refine the specifications.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        # Create the initial Universe and display it.
        Sim.initialize()
        Sim.display()

        #.Simulate and display LAST_GEN additional generations.
```

☞ **Program top-down, outside-in.**

Refine the specifications.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        # Create the initial Universe and display it.
        Sim.initialize()
        Sim.display()

        # Simulate and display LAST_GEN additional generations.
        for Sim.generation in range(1, Sim.LAST_GEN + 1):
            Sim.next_generation()
            Sim.display()
```

☞ **Program top-down, outside-in.**

`initialize`, `display`, and `next_generation` are other class methods to be defined. Class methods are always invoked using their qualified names, e.g., `Sim.display()`.

Refine the specifications.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        # Create the initial Universe and display it.
        Sim.initialize()
        Sim.display()

        # Simulate and display LAST_GEN additional generations.
        for Sim.generation in range(1, Sim.LAST_GEN + 1):
            Sim.next_generation()
            Sim.display()
```

☞ **Many short procedures are better than large blocks of code.**

Method specifications use a syntactic construct known as a "docstring".

Refine the specifications.

```
class Sim:

    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        # Create the initial Universe and display it.
        Sim.initialize()
        Sim.display()

        # Simulate and display LAST_GEN additional generations.
        for Sim.generation in range(1, Sim.LAST_GEN + 1):
            Sim.next_generation()
            Sim.display()
```

Create stubs for the methods that have been introduced, which you can do mindlessly.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universes old."""
        pass
    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        pass
    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        pass
```

☞ **Defer challenging code for later; do the easy parts first.**

The simulation of a cellular automaton models a finite M-by-N Universe of cells. The states of each `generation` of `next` cells is determined from the states of the `old` cells, where generations are numbered from 0 through `LAST_GEN`. The state of each cell is modeled as an **`int`**.

Specify and declare the data representation.

```
class Sim:

    M: int = 5                              # Height of Universe.
    N: int = 20                             # Width of Universe.
    old: list[list[int]]  = []              # old Universe.
    next: list[list[int]] = []              # next Universe.
    LAST_GEN: int = 40                      # Last generation.
    generation: int = 0                     # Generation number.

    ...
```

☞ **Aggregate the definitions of related variables and methods in a class.**

The simulation of a cellular automaton models a finite M-by-N Universe of cells. The states of each generation of next cells is determined from the states of the old cells, where generations are numbered from 0 through LAST_GEN. The state of each cell is modeled as an **int**.

N.B. The term "state" is overloaded. Each cell of the Universe has a "state".

Specify and declare the data representation.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[int]]  = []          # old Universe.
    next: list[list[int]] = []          # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.

    ...
```

☞ **Introduce program variables whose values describe "state".**

The simulation of a cellular automaton models a finite M-by-N Universe of cells. The states of each generation of next cells is determined from the states of the old cells, where generations are numbered from 0 through LAST_GEN. The state of each cell is modeled as an **int**.

N.B. The term "state" is overloaded. Each cell of the Universe has a "state", and the simulation as a whole has a "state".

Specify and declare the data representation.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[int]]  = []          # old Universe.
    next: list[list[int]] = []          # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.

    ...
```

☞ **Introduce program variables whose values describe "state".**

Specify and declare the data representation.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[int]]  = []          # old Universe.
    next: list[list[int]] = []          # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.

    ...
```

Names of variables intended to be constant throughout program execution are, by convention, all capital letters.

☞ **Minimize use of literal numerals in code; define and use symbolic constants.**

Specify and declare the data representation.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[int]]  = []          # old Universe.
    next: list[list[int]] = []          # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.

    ...
```

Variables declared and initialized at the top-level of a class are called *class variables*, and are shared among all methods of the class.

Specify and declare the data representation.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[int]]  = []          # old Universe.
    next: list[list[int]] = []          # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.

    ...
```

The initial value of the 2-D array must be created in method initialize because the needed construct (list comprehension) is not permitted here.

Specify and declare the data representation.

```
class Sim:

    M: int = 5                                  # Height of Universe.
    N: int = 20                                 # Width of Universe.
    old: list[list[int]]  = []                  # old Universe.
    next: list[list[int]] = []                  # next Universe.
    LAST_GEN: int = 40                          # Last generation.
    generation: int = 0                         # Generation number.

    ...
```

The initial value of the 2-D array must be created in method initialize because the needed construct (list comprehension) is not permitted here.

Technically, initialization to [] is a violation of the representation invariant because [] is not M-by-N.

We now turn to implementation of the methods: `initialize`.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        pass

    ...
```

We now turn to implementation of the methods: `initialize`.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        #.Initialize old and next Universes to M-by-N arrays of 0.

    ...
```

We now turn to implementation of the methods: `initialize`.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        # Initialize old and next Universes to M-by-N arrays of 0.
        Sim.old =  [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]
        Sim.next = [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]

    ...
```

Long lines can be split if between matched parentheses or brackets.

We now turn to implementation of the methods: `initialize`.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        # Initialize old and next Universes to M-by-N arrays of 0.
        Sim.old =  [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]
        Sim.next = [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]

    ...
```

We now turn to implementation of the methods: `initialize`.

```
class Sim:
    ...

    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        # Initialize old and next Universes to M-by-N arrays of 0.
        Sim.old =  [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]
        Sim.next = [[0 for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]

    ...
```

The temporary violation of the representation invariant has now been corrected.

Turn to implementing method `display`.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        pass

    ...
```

Turn to implementing method `display`.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        ____________

    ...
```

Use a standard row-major-order traversal.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

☞ **Master stylized code patterns, and use them.**

Use a standard row-major-order traversal, output cells.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

☞ **Master stylized code patterns, and use them.**

Use a standard row-major-order traversal, output cells, and output newlines at row ends.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

☞ **Master stylized code patterns, and use them.**

Use a standard row-major-order traversal, output cells, and output newlines at row ends.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

Means: Don't go to the beginning of the next line after printing.

☞ **Master stylized code patterns, and use them.**

Use a standard row-major-order traversal, output cells, and output newlines at row ends.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

Variables `r` and `c` are local variables of method `display`.
Use local variables without qualification.

Use a standard row-major-order traversal, output cells, and output newlines at row ends.

```
class Sim:
    ...

    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()

    ...
```

Variables `generation`, `M`, `N`, and `old` are class variables.
Use class variables with qualified names.

A method stub may suffice for a program test.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        pass
    ...
```

☞ **Write degenerate program stubs that allow partial programs to execute.**

Test early and often.

To try it out, invoke `Sim.main()`.

- ☞ **Test programs incrementally.**
- ☞ **Never be (very) lost. Don’t stray far from a correct (albeit, partial) program.**

Output:

```
Generation: 0
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
Generation: 1
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
Generation: 2
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
Etc.
```

What has been validated?

- Generation counting
- Array creation and initialization
- Formatting of output

☞ **Validate output thoroughly.**

We now turn to implementation of the method stub: `next_generation`.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        pass

    ...
```

☞ **Master stylized code patterns, and use them.**

Instance of the standard *compute-use* pattern.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        #.Determine the states of next[][] as F(old[][] states).
        #.Swap old[][] and next[][] Universes.
```

☞ **Master stylized code patterns, and use them.**

Standard row-major-order traversal for determining new states of each cell of next.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
```


```
        #.Swap old[][] and next[][] Universes.
```

next_generation

Standard row-major-order traversal for determining new states of each cell of next.

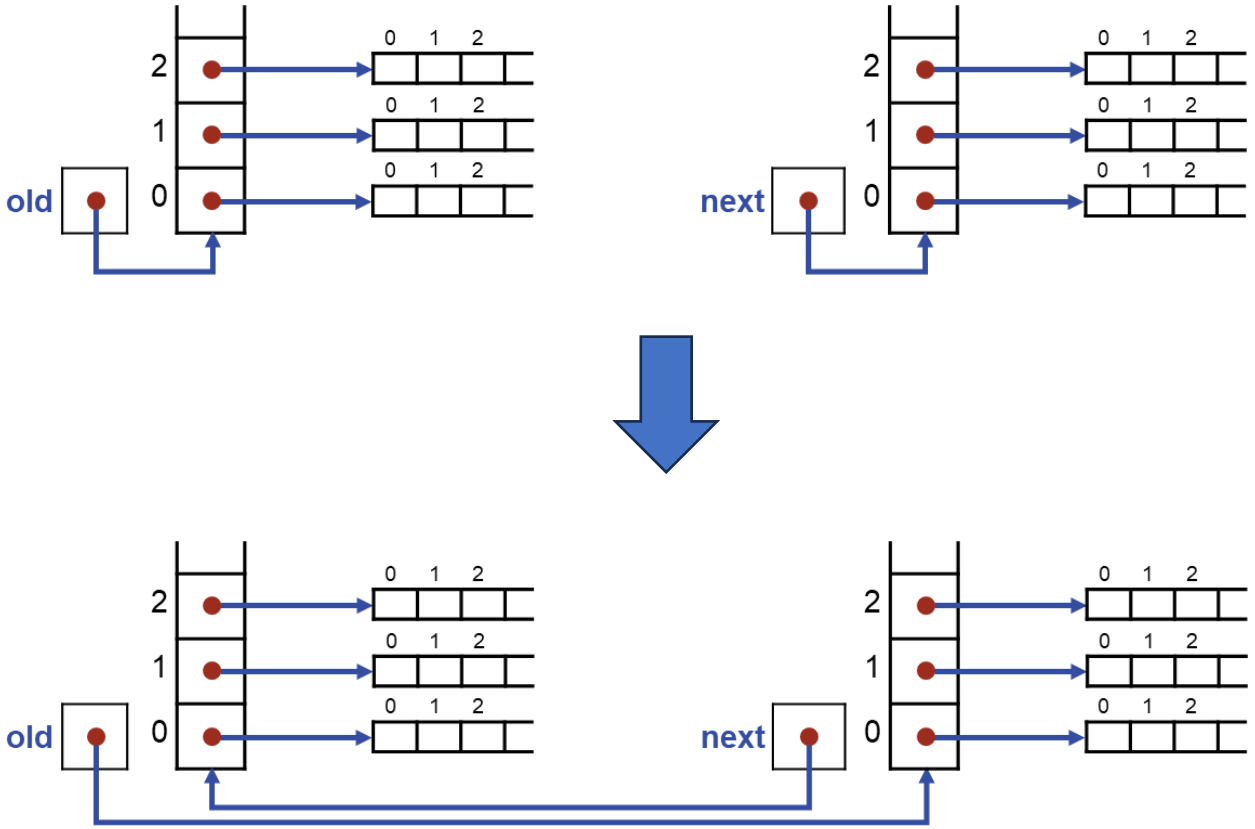
```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                # Sim.next[r][c] = F(Sim.old[r][c] and its neighbors)

        #.Swap old[][] and next[][] Universes.
```

Standard code for swap

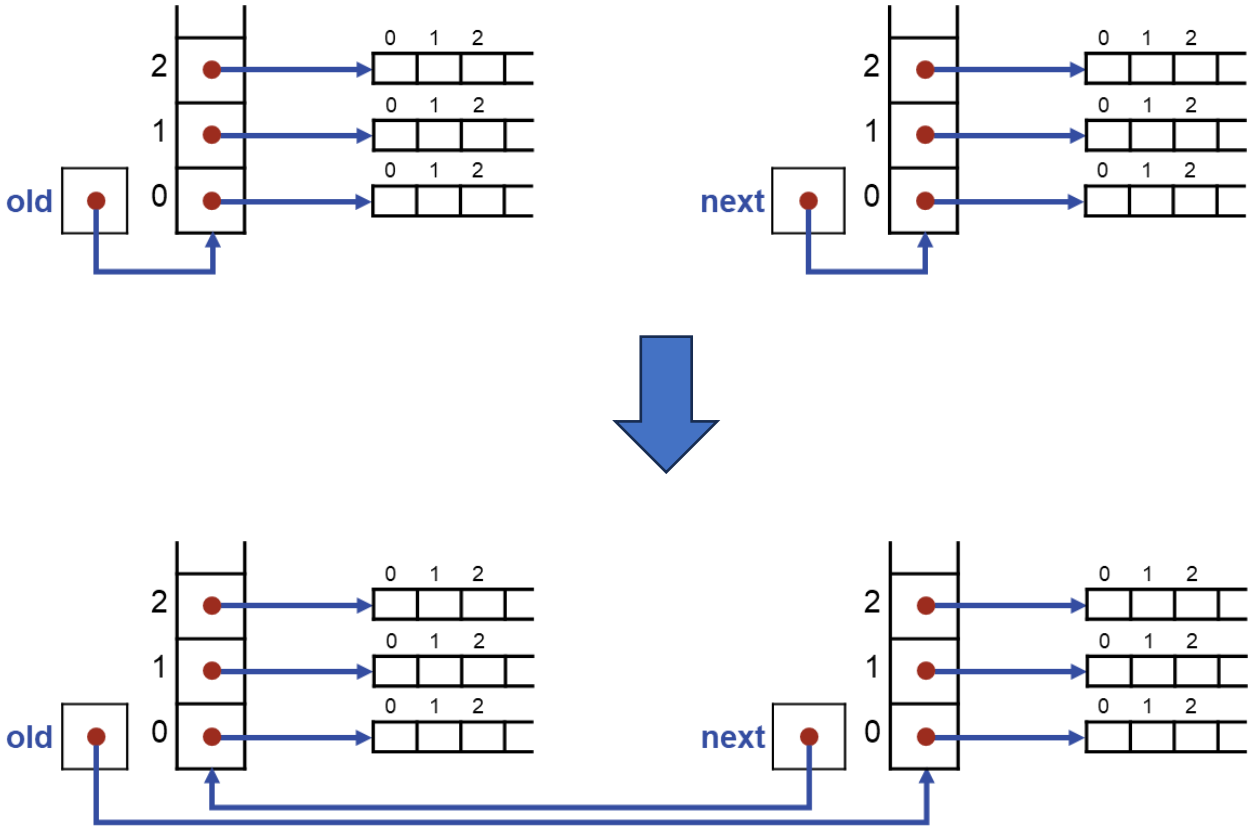
```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                # Sim.next[r][c] = F(Sim.old[r][c] and its neighbors)

        # Swap old[][] and next[][] Universes.
        temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

☞ **Master stylized code patterns, and use them.**

Notice that swap is a constant-time operation, independent of the size of the Universes.



Notice that swap is a constant-time operation, independent of the size of the Universes.*



***C/C++** Constant-time swap is not available for C-style arrays in C/C++. Rather, this can be read as describing one of the alternatives to C-style arrays that are available in C++.

Completed next_generation for a generic cellular automaton.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                # Sim.next[r][c] = F(Sim.old[r][c] and its neighbors)

        # Swap old[][] and next[][] Universes.
        temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

For easy immediate testing, let each cell increment its state on each generation.

```
class Sim:
    ...

    @classmethod
    def next_generation(cls) -> None:
        """Update Universe to be the next generation."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                Sim.next[r][c] = Sim.old[r][c] + 1

        # Swap old[][] and next[][] Universes.
        temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

☞ **Test programs incrementally.**

Test early and often.

To try it out again, invoke `Sim.main()`.

- ☞ **Test programs incrementally.**
- ☞ **Never be (very) lost. Don’t stray far from a correct (albeit, partial) program.**

Output:

```
Generation: 0
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
0000000000000000000
Generation: 1
1111111111111111111
1111111111111111111
1111111111111111111
1111111111111111111
1111111111111111111
Generation: 2
2222222222222222222
2222222222222222222
2222222222222222222
2222222222222222222
2222222222222222222
Etc.
```

What has been validated?

- Generation counting
- Array creation and initialization
- Formatting of output
- Creation of `next` Universe from `old` Universe
- Swapping of `old` and `next` Universes

☞ **Validate output thoroughly.**

Game of Life. A Cellular Automaton in which each cell is either dead or alive.

In each generation:

- Each live cell with 2 or 3 live neighbors lives on to the next generation (life) otherwise it dies (death).
- Each dead cell with 3 live neighbors comes alive in the next generation (birth) otherwise it remains dead.

Each cell is either dead or alive, so specialize the Universes as Boolean 2-D arrays.

```
class Sim:

    M: int = 5                              # Height of Universe.
    N: int = 20                             # Width of Universe.
    old: list[list[bool]]  = []             # old Universe.
    next: list[list[bool]] = []             # next Universe.
    LAST_GEN: int = 40                      # Last generation.
    generation: int = 0                     # Generation number.

    ...
```

☞ **Choose representations that by design don't have nonsensical configurations.**

Revise method `initialize` similarly.

```
class Sim:
    ...
    @classmethod
    def initialize(cls) -> None:
        """Create the initial Universe."""
        # Initialize old and next Universes to M-by-N arrays of False.
        Sim.old =  [[False for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]
        Sim.next = [[False for _ in range(0, Sim.N)]
                    for _ in range(0, Sim.M)]
    ...
```

☞ **Choose representations that by design don't have nonsensical configurations.**

Revise method `display` to compactly render dead as "_" and alive as "X".

```
class Sim:
    ...
    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N): print(Sim.old[r][c], end='')
            print()
    ...
```

Revise method `display` to compactly render dead as “_” and alive as “X“.

```
class Sim:
    ...
    @classmethod
    def display(cls) -> None:
        """Display the present Universe."""“
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                if Sim.old[r][c]: print("X", end='')
                else: print("_", end='')
            print()
    ...
```

While we are at it, revise the method header to be more informative.

```
class Sim:
    ...
    @classmethod
    def display(cls) -> None:
        """Display Universe old[][] as an M-by-N grid."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                if Sim.old[r][c]: print("X", end='')
                else: print("_", end='')
            print()
    ...
```

☞ **Repeatedly improve comments by relentless copy editing.**

That way, for example, the tip provided in an IDE editor will be more helpful.

```
class Sim:
    ...
    @classmethod
    def main(cls) -> None:
        """Simulate a cellular automaton."""
        # Create the initial Universe and display it.
        Sim.initialize()
        Sim.display()

        # Simula                                    ning generations.
        for Sim.                                    ST_GEN + 1):
            Sim.
            Sim.display()
```

```
@classmethod
def display(cls) -> None

Display Universe old[][] as an M-by-N grid.
```

☞ **Repeatedly improve comments by relentless copy editing.**

Similarly, turn end-of-line comments of variable declarations into docstrings.

```
class Sim:

    M: int = 5                          # Height of Universe.
    N: int = 20                         # Width of Universe.
    old: list[list[bool]]  = []         # old Universe.
    next: list[list[bool]] = []         # next Universe.
    LAST_GEN: int = 40                  # Last generation.
    generation: int = 0                 # Generation number.
```

☞ **Repeatedly improve comments by relentless copy editing.**

Similarly, you can turn end-of-line comments of variable declarations into docstrings.

```
class Sim:

    M: int = 5
    """M is the height of the Universe."""

    N: int = 20
    """N is the width of the Universe."""

    old: list[list[bool]]  = []
    """old is the present state of the Universe."""

    next: list[list[bool]] = []
    """next is the upcoming generation of the Universe, in preparation."""

    LAST_GEN: int = 40
    """LAST_GEN is last generation to be simulated."""

    generation: int = 0
    """generation is the number of the present generation."""
```

The docstring of a variable is the variable's representation invariant.

```
class Sim:
    ...
    @classmethod
    def display(cls) -> None:
        """Display Universe old[][] as an M-by-N grid."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0,
                if Sim.old[r]
                else: print("_
            print()
    ...
```

```
class attribute M of Sim
M: int = 5
```

M is the height of the Universe.

☞ **Repeatedly improve comments by relentless copy editing.**

The docstring of a variable is the variable's representation invariant.

```
class Sim:
    ...
    @classmethod
    def display(cls) -> None:
        """Display Universe old[][] as an M-by-N grid."""
        print( "Generation: ", Sim.generation )
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                if Sim.old[r][c]: print("X", end='')
                else:
            print()
    ...
```

```
class attribute old of Sim
old: list[list[bool]] = []

old is the present state of the Universe.
```

☞ **Repeatedly improve comments by relentless copy editing.**

Implement the Game of Life rules.

```
class Sim:
    ...
    @classmethod
    def next_generation(cls) -> None:
        """Update old[][] to be the next generation of the Universe."""
        # Determine the states of next[][] as F(old[][] states).
        for r in range(0, Sim.M):
            for c in range(0, Sim.N):
                # Set next[r][c] = according to the Game of Life rules.

        # Swap old[][] and next[][] Universes.
        temp = Sim.old;  Sim.old = Sim.next;  Sim.next = tem
```

Refine the specification using the standard *compute-use* pattern.

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            #.Compute.
            #.Use.

    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

☞ **Master stylized code patterns, and use them.**

Instantiate placeholders *Compute* and *Use* for the problem at hand.

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            #.Let liveNeighbors be # of alive cells around old[r][c].
            #.Set next[r][c] based on old[r][c] and liveNeighbors.
    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

☞ **Master stylized code patterns, and use them.**

Use is a structured four-way case analysis.

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            #.Let liveNeighbors be # of alive cells around old[r][c].

            # Set next[r][c] based on old[r][c] and liveNeighbors.
            if Sim.old[r][c]:  # Currently live.
                if (live_neighbors == 2) or (live_neighbors == 3):
                    Sim.next[r][c] = True
                else: Sim.next[r][c] = False
            else:  # Currently dead.
                if live_neighbors == 3:
                    Sim.next[r][c] = True
                else: Sim.next[r][c] = False

    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp
```

Compute is a 3x3 row-major-order traversal, counting `live_neighbors` as appropriate.

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            # Let liveNeighbors be # of alive cells around old[r][c].
            live_neighbors = 0
            for dr in range(-1, 2):
                for dc in range(-1, 2):
                    if not((dr == 0) and (dc == 0)) and (
                            Sim.old[r + dr][c + dc] ):
                        live_neighbors += 1

            # Set next[r][c] based on old[r][c] and liveNeighbors.
            ...

    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp;
```

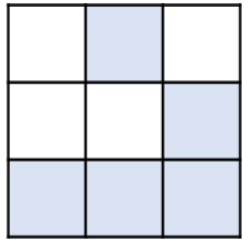
To prevent the subscripts from going out of bounds

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            # Let liveNeighbors be # of alive cells around old[r][c].
            live_neighbors = 0
            for dr in range(-1, 2):
                for dc in range(-1, 2):
                    if not((dr == 0) and (dc == 0)) and (
                        Sim.old[r + dr][c + dc] ):
                            live_neighbors += 1

            # Set next[r][c] based on old[r][c] and liveNeighbors.
            ...

    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp;
```

To prevent the subscripts from going out of bounds, simulate on a torus.

```
@classmethod
def next_generation(cls) -> None:
    """Update old[][] to be the next generation of the Universe."""
    # Determine the states of next[][] as F(old[][] states).
    for r in range(0, Sim.M):
        for c in range(0, Sim.N):
            # Let liveNeighbors be # of alive cells around old[r][c].
            live_neighbors = 0
            for dr in range(-1, 2):
                for dc in range(-1, 2):
                    if not((dr == 0) and (dc == 0)) and (
                        Sim.old[(r + dr) % Sim.M][(c + dc) % Sim.N] ):
                            live_neighbors += 1

            # Set next[r][c] based on old[r][c] and liveNeighbors.
            ...

    # Swap old[][] and next[][] Universes.
    temp = Sim.old;  Sim.old = Sim.next;  Sim.next = temp;
```

Create some life, which will glide diagonally down and to the right.



```
@classmethod
def initialize(cls) -> None:
    """Create the initial Universe."""“
    # Initialize old and next Universes to M-by-N arrays of False.
        ...
    # Glider
    Sim.old[0][1] = True
    Sim.old[1][2] = True
    Sim.old[2][0] = True
    Sim.old[2][1] = True
    Sim.old[2][2] = True
```

To let it rip, invoke `Sim.main()` yet again.

And presto …

```
Generation: 0
_X__________________
__X_________________
XXX_________________
____________________
____________________
```

And presto …

```
Generation:  1
____________________
X_X_________________
_XX_________________
_X__________________
____________________
```

And presto …

```
Generation:  2
____________________
__X_________________
X_X_________________
_XX_________________
____________________
```

And presto …

```
Generation:  3
_____________________
_X___________________
__XX_________________
_XX__________________
_____________________
```

And presto …

```
Generation:  4
____________________
__X_________________
___X________________
_XXX________________
____________________
```

Back to the same configuration as Generation 0, but shifted down and right one cell.

And presto …

```
Generation:  5
____________________
____________________
_X_X________________
__XX________________
__X_________________
```

And presto …

```
Generation:  6
____________________
____________________
___X________________
_X_X________________
__XX________________
```

And presto …

```
Generation:  7
____________________
____________________
__X_________________
___XX_______________
__XX________________
```

And presto …

```
Generation:  8
____________________
____________________
___X________________
____X_______________
__XXX_______________
```

Back to the same configuration as Generation 1, but shifted down and right one cell.

And presto …

```
Generation:  9
___X_____________________
________________________
________________________
__X_X___________________
___XX____________________
```

Whoa! What's going on? Oh, I forgot, we are on a torus.

And presto …

```
Generation:  10
___XX_____________
____________________
____________________
____X_____________
__X_X_____________
Generation:  11
```

And presto …

```
Generation:  11
___XX_____________
____________________
____________________
___X_____________
____XX____________
```

And presto …

```
Generation:  12
___XXX_____________
____________________
____________________
____X_______________
_____X______________
```

And presto …

```
Generation:  13
____XX______________
____X_______________
____________________
____________________
___X_X______________
```

And presto …

```
Generation:  14
___X_X_____________
____XX_____________
____________________
____________________
_____X_____________
```

And presto …

```
Generation:  15
_____XX______________
____XX_______________
____________________
____________________
____X_______________
```

And presto …

```
Generation:  16
______X______________
____XXX______________
____________________
____________________
_____X_______________
```

And presto …

```
Generation:  17
____X_X_____________
_____XX_____________
_____X______________
____________________
____________________
```

And presto …

```
Generation:  18
______X______________
____X_X______________
_____XX______________
____________________
____________________
```

And presto …

```
Generation:  19
_____X_____________
______XX___________
_____XX____________
____________________
____________________
```

And presto …

```
Generation:  20
______X______________
_______X_____________
_____XXX_____________
____________________
____________________
```

Back to the same configuration as Generation 0, but shifted right several cells. The glider is coiling around the donut!

What are the boundary conditions for this problem, and did we forget them?

For example, what if the height of the Universe were only 4? To try it out, change N, and invoke `Sim.main()`.

```
Generation: 0
_X__________________
__X_________________
XXX_________________
____________________
```

☞ **Boundary conditions. Dead last, but don't forget them.**

What are the boundary conditions for this problem, and did we forget them?

For example, what if the height of the Universe were only 4? To try it out, change N, and invoke `Sim.main()`.

```
Generation: 0
_X_____________________
__X____________________
XXX____________________
_______________________
Generation:  1
_______________________
X_X____________________
_XX____________________
X_X____________________
```

There isn't enough "elbowroom" around the glider, and it is interfering with its own propagation. By generation 6, all life is gone!

Should your program be defensive and prevent this, or is this just how life goes?

☞ **Boundary conditions. Dead last, but don't forget them.**

Summary:

The notion of a **class** has been introduced as a means for aggregating variables and methods.

Many standard precepts, patterns, and recommended coding techniques have been illustrated.

Representation invariants for data structures and their components have been emphasized, and their effective use in IDE's shown.

And the Game of Life itself is fascinating.