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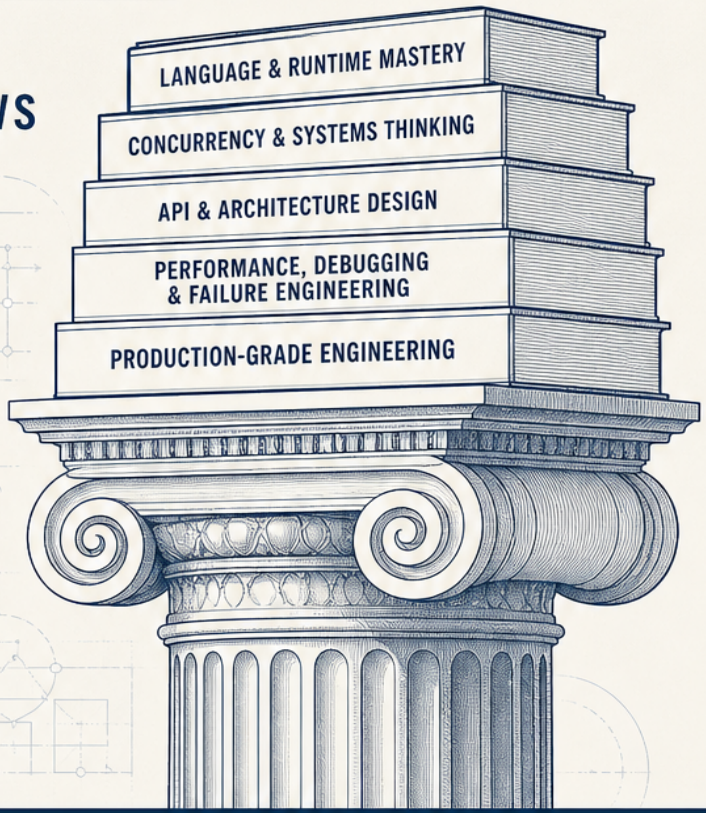

BUILT FOR REAL-WORLD ENGINEERS.

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```
ob_refcnt
ob_type
```

```
def func(x: int) -> list[int]:
    for i in range(x):
        yield i
```

DEEP LANGUAGE KNOWLEDGE | CONCURRENCY & SYSTEMS MASTERY | ARCHITECTURE & API DESIGN | PERFORMANCE & DEBUGGING | RELIABILITY & SECURITY

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Staff Level Python Mastery - A Reference Guide

For Senior & Staff Engineering Interviews

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Chapter 1 — The Python Object Model

1.1 Everything Is an Object

In CPython, every entity the language can name — integers, strings, functions, classes, modules, `None`, even `type` itself — is a heap-allocated C struct of type `PyObject`. That struct contains at minimum two fields: a reference count (`ob_refcnt`) and a pointer to the object's type (`ob_type`). All Python-level behavior is dispatched through the type object.

```
>>> type(42)
<class 'int'>
>>> type(int)
<class 'type'>
>>> type(type)
<class 'type'>          # type is its own metaclass
>>> isinstance(int, type)
True
>>> isinstance(int, object)
True
```

The universal base: every class implicitly inherits from `object`. `type` itself inherits from `object`, and `object`'s type is `type`. This circularity is bootstrapped at interpreter startup and is a known intentional design.

Practical implication: You can attach attributes to instances of user-defined classes arbitrarily, because every such instance has a `__dict__` (unless `__slots__` is used). Functions are objects with `__name__`, `__doc__`, `__defaults__`, `__annotations__`, `__code__`, and `__closure__`. You can inspect, modify, and pass them freely.

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1.2 Attribute Lookup: The Full Resolution Order

When Python evaluates `obj.attr`, it does not simply look in a dictionary. It follows a precise chain, delegating to the type system at each step.

1.2.1 The MRO (Method Resolution Order)

For inheritance, Python uses the **C3 Linearization** algorithm to compute a consistent, deterministic MRO. The MRO is stored in `ClassName.__mro__` as a tuple of classes.

```
class A: pass
class B(A): pass
class C(A): pass
class D(B, C): pass

print(D.__mro__)
# (<class 'D'>, <class 'B'>, <class 'C'>, <class 'A'>, <class 'object'>)
```

C3 guarantees: (1) a class always precedes its parents; (2) the order among parents is preserved; (3) monotonicity – if C comes before D in any class's MRO, that ordering holds throughout.

An inconsistent hierarchy raises `TypeError` at class definition time:

```
class X(A, object): pass   # fine
class Y(object, A): pass   # fine
class Z(X, Y): pass        # TypeError: Cannot create a consistent MRO
```

1.2.2 The Descriptor Protocol — The Core of Attribute Lookup

The full attribute lookup algorithm for `obj.attr` (where `type(obj)` is `T`):

1. Search `T.__mro__` for `attr`. Call the first class that defines it `B`, and the found object `descriptor`.
2. If `descriptor` is a **data descriptor** (defines both `__get__` and `__set__`, or `__get__` and `__delete__`): return `descriptor.__get__(obj, T)`. Data descriptors take priority over the instance `__dict__`.
3. If `attr` is in `obj.__dict__`: return `obj.__dict__['attr']`. Instance dictionary beats non-data descriptors.
4. If `descriptor` is a **non-data descriptor** (defines `__get__` only): return `descriptor.__get__(obj, T)`.
5. If `descriptor` exists but defines neither `__get__` nor `__set__`: return `descriptor` itself.

6. Raise `AttributeError`.

Why this matters:

- `@property` is a data descriptor (it defines `__get__`, `__set__`, and `__delete__`), which is why it takes priority over the instance `__dict__`. You cannot shadow a property by setting `self.x = ...` unless the property's `__set__` allows it.
- Functions are non-data descriptors (they define `__get__` but not `__set__`). That is how method binding works: `obj.method` calls `function.__get__(obj, type(obj))`, which returns a bound method that prepends `obj` as the first argument.
- `staticmethod` and `classmethod` are also descriptors – they override `__get__` to return the raw function or a class-bound callable respectively.

1.2.3 Writing a Descriptor

```python
class Validated:
    """Data descriptor that enforces a type constraint."""

    def __set_name__(self, owner, name):
        # Called at class creation time; `name` is the attribute name.
        self.public_name = name
        self.private_name = '_' + name

    def __get__(self, obj, objtype=None):
        if obj is None:
            # Accessed on the class itself, return the descriptor.
            return self
        return getattr(obj, self.private_name, None)

    def __set__(self, obj, value):
        self.validate(value)
        setattr(obj, self.private_name, value)

    def validate(self, value):
        raise NotImplementedError


class PositiveInt(Validated):
    def validate(self, value):
        if not isinstance(value, int) or value <= 0:
            raise ValueError(f"Expected positive int, got {value!r}")
```

```python


class Connection:
    max_retries = PositiveInt()
    timeout = PositiveInt()

    def __init__(self, max_retries, timeout):
        self.max_retries = max_retries   # calls PositiveInt.__set__
        self.timeout = timeout


c = Connection(3, 30)
c.max_retries = -1   # raises ValueError
```

Key points:

- `__set_name__` is called by `type.__new__` during class body execution; it grants the descriptor knowledge of the attribute name without manual configuration.
- When accessed on the class (`Connection.max_retries`), `obj` is `None` inside `__get__`. Returning `self` lets you inspect the descriptor itself.
- The private name convention (`_max_retries`) avoids infinite recursion: `setattr(obj, self.private_name, value)` writes directly to `obj.__dict__`, bypassing the descriptor.

* * *

1.3 Special Methods (Dunder Methods)

Special methods are looked up on the **type**, not the instance. This is a critical distinction:

```
class Weird:
    def __len__(self):
        return 42

w = Weird()
w.__len__ = lambda: 0      # patching the instance
len(w)                     # still returns 42 — type lookup, not instance
```

This prevents user-defined objects from accidentally or maliciously bypassing the protocol by patching individual instances.

1.3.1 Construction and Lifecycle

`__new__(cls, *args, **kwargs)` – allocates and returns the new instance. It is a static method implicitly. It runs before `__init__`. If it returns something that is not an instance of `cls`, `__init__` is not called.

```
class Singleton:
    _instance = None

    def __new__(cls, *args, **kwargs):
        if cls._instance is None:
            cls._instance = super().__new__(cls)
        return cls._instance
```

`__init__(self, *args, **kwargs)` – initialises the already-allocated instance. Return value must be `None`; returning anything else raises `TypeError`.

`__del__(self)` – finalizer, called when the reference count drops to zero (or by the cyclic GC). Unreliable for resource cleanup; do not depend on it for correctness. Prefer `__exit__` via context managers.

1.3.2 Representation

`__repr__(self)` – unambiguous machine-readable string. Should ideally return a string that, when `eval`'d, reconstructs the object. Used in the REPL, `repr()`, logging, and as a fallback for `__str__`.

`__str__(self)` – human-readable string. Used by `str()`, `print()`, and f-string `{obj}`. Falls back to `__repr__` if not defined.

`__format__(self, format_spec)` – called by `format()` and f-string `{obj:spec}`. Allows custom format mini-languages (see `datetime`, `Decimal`).

```python
class Vector:
    def __init__(self, x, y):
        self.x = x
        self.y = y

    def __repr__(self):
        return f"Vector({self.x!r}, {self.y!r})"

    def __str__(self):
        return f"({self.x}, {self.y})"

    def __format__(self, spec):
        if spec == 'polar':
            r = (self.x**2 + self.y**2) ** 0.5
            return f"|{r:.3f}|"
        return str(self)
```

1.3.3 Comparison and Hashing

The **hash/equality contract**: objects that compare equal must have the same hash. Formally: if `a == b` then `hash(a) == hash(b)`. The converse is not required.

In Python:

- If you define `__eq__`, Python sets `__hash__` to `None` by default (making the class unhashable), because Python cannot know if your equality relation is compatible with any hash function.
- You must explicitly define `__hash__` alongside `__eq__`.
- If you inherit `__eq__` from a parent and want the inherited `__hash__`, you must explicitly restore it: `__hash__ = ParentClass.__hash__`.

```python
class Point:
    def __init__(self, x, y):
        self.x = x
        self.y = y

    def __eq__(self, other):
        if not isinstance(other, Point):
            return NotImplemented
        return self.x == other.x and self.y == other.y

    def __hash__(self):
        return hash((self.x, self.y))
```

Returning `NotImplemented` (not `NotImplementedError`) from comparison operators tells Python to try the reflected operation on the other operand. This is required for correct interoperability:

```python
class MyNum:
    def __eq__(self, other):
        if not isinstance(other, MyNum):
            return NotImplemented   # let `other.__eq__(self)` be tried
        ...
```

`functools.total_ordering` – if you define `__eq__` and one of `__lt__`, `__le__`, `__gt__`, `__ge__`, it fills in the rest. Use with care: it has a performance overhead and is disabled in some internal CPython types. Acceptable in interview code.

```python
from functools import total_ordering

@total_ordering
class Priority:
    def __init__(self, value):
        self.value = value

    def __eq__(self, other):
        return self.value == other.value

    def __lt__(self, other):
        return self.value < other.value

    # __le__, __gt__, __ge__ are auto-generated
```

1.3.4 Container Emulation

```python
class RingBuffer:
    """Fixed-size circular buffer demonstrating container protocol."""

    def __init__(self, capacity):
        self._capacity = capacity
        self._buffer = [None] * capacity
        self._head = 0
        self._size = 0

    def append(self, item):
        idx = (self._head + self._size) % self._capacity
        if self._size < self._capacity:
            self._buffer[idx] = item
            self._size += 1
        else:
            # Overwrite oldest
            self._buffer[self._head] = item
            self._head = (self._head + 1) % self._capacity

    def __len__(self):
        return self._size

    def __getitem__(self, index):
        if index < 0:
            index += self._size
        if not (0 <= index < self._size):
            raise IndexError("index out of range")
        return self._buffer[(self._head + index) % self._capacity]

    def __contains__(self, item):
        # O(n); override for custom membership semantics
        return any(self[i] == item for i in range(self._size))

    def __iter__(self):
        for i in range(self._size):
            yield self[i]

    def __repr__(self):
        return f"RingBuffer({list(self)!r})"
```

Notes:

- `__len__` must return a non-negative integer. `bool(obj)` falls back to `__len__` if `__bool__` is not defined; empty containers are falsy.
- `__contains__` is optional; Python falls back to iterating via `__iter__` if absent.
- `__iter__` returning a generator is idiomatic and sufficient for most

use cases. For persistent iterators (multiple independent iterations), implement `__iter__` to return a new iterator object each time.

- `__getitem__` with integer indices and raising `IndexError` is sufficient for `for` loops even without `__iter__` (the legacy iteration protocol).

1.3.5 Callable Objects

```
class Memoize:
    """Callable object wrapping a function with a result cache."""

    def __init__(self, func):
        self._func = func
        self._cache = {}
        # Preserve metadata for introspection
        import functools
        functools.update_wrapper(self, func)

    def __call__(self, *args):
        if args not in self._cache:
            self._cache[args] = self._func(*args)
        return self._cache[args]

    def cache_clear(self):
        self._cache.clear()
```

1.3.6 Context Managers

The context manager protocol: `__enter__` runs on entry to the `with` block and its return value is bound to the `as` target; `__exit__(self, exc_type, exc_val, exc_tb)` runs on exit. If `__exit__` returns a truthy value, any exception is suppressed.

```python
class ManagedConnection:
    def __init__(self, dsn):
        self.dsn = dsn
        self.conn = None

    def __enter__(self):
        self.conn = connect(self.dsn)   # hypothetical
        return self.conn                # bound to `as` target

    def __exit__(self, exc_type, exc_val, exc_tb):
        if exc_type is not None:
            self.conn.rollback()
        else:
            self.conn.commit()
        self.conn.close()
        return False   # do not suppress exceptions
```

Suppression example — useful in tests or resilient loops:

```python
def __exit__(self, exc_type, exc_val, exc_tb):
    if exc_type is KeyError:
        return True    # suppress only KeyError
    return False
```

`contextlib.contextmanager` transforms a generator function into a context manager without a class:

```python
from contextlib import contextmanager

@contextmanager
def temp_directory():
    import tempfile, shutil
    path = tempfile.mkdtemp()
    try:
        yield path
    finally:
        shutil.rmtree(path)
```

The code before `yield` is `__enter__`; the `yield` value is the `as` target; the code after is `__exit__`. The `finally` ensures cleanup even on exception.

* * *

1.4 `__slots__`

By default, each instance of a user-defined class has a `__dict__` – a hash table allocated per instance. For classes with many instances and a fixed set of attributes, this wastes significant memory.

`__slots__` replaces `__dict__` with a fixed set of slot descriptors stored at the class level:

```
class Point:
    __slots__ = ('x', 'y')

    def __init__(self, x, y):
        self.x = x
        self.y = y
```

Consequences of `__slots__`:

- No `__dict__` on instances (unless `'__dict__'` is listed in `__slots__`).
- No `__weakref__` unless `'__weakref__'` is listed.
- Cannot add arbitrary attributes at runtime.
- Memory reduction is approximately 40–50% for small objects in CPython (varies by attribute count).
- **Inheritance caveat:** If a parent class does not use `__slots__`, the subclass still has `__dict__` (inherited from the parent). `__slots__` only blocks `__dict__` creation when the entire MRO uses it.

```
import sys

class WithDict:
    def __init__(self):
        self.x = 1
        self.y = 2

class WithSlots:
    __slots__ = ('x', 'y')
    def __init__(self):
        self.x = 1
        self.y = 2

print(sys.getsizeof(WithDict()))    # ~48 bytes + dict overhead (~232 bytes)
print(sys.getsizeof(WithSlots()))   # ~56 bytes (slots stored compactly)
```

* * *

1.5 Function Objects in Depth

Functions in Python are first-class objects of type `function`. Their key attributes:

Attribute	Contents
`__name__`	Unqualified function name
`__qualname__`	Qualified name (includes enclosing scope, e.g., `Class.method`)
`__doc__`	Docstring
`__module__`	Module in which the function was defined
`__defaults__`	Tuple of default values for positional params; `None` if none
`__kwdefaults__`	Dict of default values for keyword-only params
`__annotations__`	Dict of parameter/return annotations
`__code__`	Code object (contains bytecode, constants, local variable names)
`__closure__`	Tuple of cell objects for free variables; `None` if no closure
`__globals__`	Reference to the module's global namespace dict

1.5.1 The Mutable Default Argument Trap

Default values are evaluated **once**, at function definition time, and stored in `__defaults__`. Mutable defaults are shared across all calls:

```python
def append_to(element, target=[]):   # BAD
    target.append(element)
    return target

append_to(1)   # [1]
append_to(2)   # [1, 2]  — same list!

def append_to(element, target=None):  # CORRECT
    if target is None:
        target = []
    target.append(element)
    return target
```

The fix uses `None` as the sentinel. This pattern is idiomatic Python.

1.5.2 Closures

A closure captures references to variables in the enclosing scope via cell objects. The reference is live — mutations in the enclosing scope are visible:

```python
def make_counter():
    count = 0
    def increment():
        nonlocal count
        count += 1
        return count
    return increment

c = make_counter()
c()   # 1
c()   # 2
```

`nonlocal` is required to rebind a variable in the enclosing scope. Without it, an assignment inside the inner function creates a new local variable (shadowing), and reading before assignment raises `UnboundLocalError`.

Classic closure-in-loop bug:

```python
fns = [lambda: i for i in range(3)]
[f() for f in fns]   # [2, 2, 2] — all capture the same `i`

# Fix: bind current value as a default argument
fns = [lambda i=i: i for i in range(3)]
[f() for f in fns]   # [0, 1, 2]
```

* * *

1.6 Attribute Access Hooks

1.6.1 `__getattr__` vs `__getattribute__`

- **`__getattribute__`** – called on *every* attribute access. Overriding it incorrectly causes infinite recursion. Call `super().__getattribute__(name)` to use the default.
- **`__getattr__`** – called only when the *normal lookup fails* (i.e., after `__getattribute__` raises `AttributeError`). This is the safe hook for computed or lazy attributes.

```python
class LazyLoader:
    """Loads a module attribute on first access."""

    def __init__(self, module_name):
        object.__setattr__(self, '_module_name', module_name)
        object.__setattr__(self, '_module', None)

    def _load(self):
        import importlib
        mod = importlib.import_module(self._module_name)
        object.__setattr__(self, '_module', mod)
        return mod

    def __getattr__(self, name):
        # Only called if `name` not found normally
        mod = self._module or self._load()
        return getattr(mod, name)
```

1.6.2 `__setattr__` and `__delattr__`

`__setattr__` is called on *every* `self.x = value`. Must use `object.__setattr__(self, name, value)` internally to avoid infinite recursion.

```python
class Immutable:
    def __init__(self, **kwargs):
        for k, v in kwargs.items():
            object.__setattr__(self, k, v)

    def __setattr__(self, name, value):
        raise AttributeError("Immutable object")

    def __delattr__(self, name):
        raise AttributeError("Immutable object")
```

* * *

1.7 `@property`, `@staticmethod`, `@classmethod`

All three are implemented as descriptors.

`@property`

```python
class Circle:
    def __init__(self, radius):
        self._radius = radius

    @property
    def radius(self):
        return self._radius

    @radius.setter
    def radius(self, value):
        if value < 0:
            raise ValueError("Radius must be non-negative")
        self._radius = value

    @radius.deleter
    def radius(self):
        del self._radius
```

```
18
19      @property
20      def area(self):
21          import math
22          return math.pi * self._radius ** 2
```

`@property` creates a data descriptor. The getter, setter, and deleter are stored as attributes of the property object. The `@radius.setter` syntax returns a *new* property object with the setter attached – it does not mutate the original.

`@classmethod`

Receives the class as first argument (conventionally `cls`). Used for alternative constructors:

```
class Date:
    def __init__(self, year, month, day):
        self.year, self.month, self.day = year, month, day

    @classmethod
    def from_iso_string(cls, s):
        # Works correctly on subclasses too – `cls` is the actual class
        year, month, day = map(int, s.split('-'))
        return cls(year, month, day)
```

`@staticmethod`

Receives neither the instance nor the class. A plain function namespaced to the class:

```
class Validator:
    @staticmethod
    def is_valid_email(email):
        return '@' in email and '.' in email.split('@')[1]
```

Choose `@staticmethod` when the method does not need access to class or instance state. Choose `@classmethod` when it needs the class (especially for subclass-aware construction). Choose a module-level function when neither is needed – avoid over-encapsulating into a class.

* * *

1.8 `__init_subclass__` and Class Hooks

Introduced in Python 3.6, `__init_subclass__` runs when a class is subclassed:

```
class Plugin:
    _registry = {}

    def __init_subclass__(cls, plugin_name=None, **kwargs):
        super().__init_subclass__(**kwargs)
        if plugin_name:
            Plugin._registry[plugin_name] = cls


class CSVPlugin(Plugin, plugin_name='csv'):
    pass

class JSONPlugin(Plugin, plugin_name='json'):
    pass

print(Plugin._registry)
# {'csv': <class 'CSVPlugin'>, 'json': <class 'JSONPlugin'>}
```

This is a lightweight alternative to metaclasses for registration patterns. The keyword argument `plugin_name` is passed at class definition time, not at instantiation.

* * *

1.9 The `object.__class__` and `type.__instancecheck__`

`isinstance(obj, cls)` is not simply `type(obj) is cls`. It calls `cls.__instancecheck__(obj)`, which is defined on the metaclass. This is how Abstract Base Classes implement virtual subclassing:

```python
from abc import ABCMeta

class Sequence(metaclass=ABCMeta):
    @classmethod
    def __subclasshook__(cls, C):
        # Return True if C should be considered a Sequence
        # even without inheriting from Sequence
        if '__getitem__' in C.__dict__ and '__len__' in C.__dict__:
            return True
        return NotImplemented
```

`__subclasshook__` is called by `ABCMeta.__subclasscheck__`. If it returns `True`, `issubclass(C, Sequence)` is `True` without explicit inheritance. This enables structural subtyping in Python's ABCs.

* * *

1.10 Object Copying

Shallow copy (`copy.copy`) – creates a new object of the same type with the same top-level attribute values. Nested objects are *not* duplicated – both copies point to the same nested objects.

Deep copy (`copy.deepcopy`) – recursively duplicates the entire object graph. Handles circular references using a memo dictionary. Expensive; avoid for large graphs.

```python
import copy

class Graph:
    def __init__(self, nodes):
        self.nodes = nodes   # list of Node objects

g1 = Graph([Node(1), Node(2)])
g2 = copy.copy(g1)      # g2.nodes is the same list object as g1.nodes
g3 = copy.deepcopy(g1)  # g3.nodes is a new list with new Node copies
```

Customising:

```python
class Node:
    def __copy__(self):
        # Custom shallow copy
        new = Node.__new__(Node)
        new.__dict__.update(self.__dict__)
        return new

    def __deepcopy__(self, memo):
        # memo maps id(original) -> copy; prevents infinite loops on cycles
        new = Node.__new__(Node)
        memo[id(self)] = new
        for k, v in self.__dict__.items():
            setattr(new, k, copy.deepcopy(v, memo))
        return new
```

* * *

1.11 Identity, Equality, and Interning

- `is` tests object identity (`id(a) == id(b)`), not value equality.
- `==` calls `__eq__`.
- CPython interns small integers (-5 to 256) and many string literals; do not rely on this behavior in production code.

```python
a = 256
b = 256
a is b   # True  — interned

a = 257
b = 257
a is b   # False — not guaranteed (though often True in same code block)

# String interning
s1 = 'hello'
s2 = 'hello'
s1 is s2   # True — interned at compile time

s1 = ''.join(['h','e','l','l','o'])
s2 = 'hello'
s1 is s2   # False — runtime-constructed string
```

The only safe uses of `is`: testing against singletons (`None`, `True`, `False`, `NotImplemented`, `Ellipsis`).

* * *

Summary of Key Principles

Concept	Rule
Attribute lookup	Data descriptor > instance `__dict__` > non-data descriptor
`__eq__` and `__hash__`	Always define both together; return `NotImplemented` not `False` for unknown types
`__repr__`	Should be unambiguous and ideally eval-able
`__getattr__`	Only fires on failure; use for lazy/dynamic attributes
`__getattribute__`	Fires on every access; override with extreme care
`__slots__`	Reduces memory; requires all classes in MRO to use it
Default arguments	Use `None` sentinel, not mutable objects
`is` operator	Only valid against singletons
Closures	Capture by reference; use default-argument trick for loop variables

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Chapter 2 — The Type System & Type Hints

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2.1 The Purpose of Type Hints in Python

Python's type system is **gradual**: type annotations are optional, carry no runtime enforcement by default, and coexist with fully untyped code. The type checker (mypy, pyright, pytype) operates as a separate offline pass — it reads the annotations and the code's structure, then reports inconsistencies without ever running the program.

This design means:

- Annotations can be added incrementally to existing codebases.
- You can annotate some functions and leave others as `Any`.
- Runtime behavior is completely unaffected by annotations (with minor exceptions noted below).

The primary value of type hints:

1. **Documentation** — a function signature is a contract that tools can verify.
2. **IDE support** — auto-complete, refactoring, and inline error detection.
3. **Correctness** — catching bugs at the boundary of system components before they manifest at runtime.
4. **Maintainability** — large codebases become navigable without reading every implementation.

At a staff level you are expected to write fully annotated code, reason about type correctness, and understand the limits of the type system.

* * *

2.2 Annotation Mechanics

2.2.1 How Annotations Are Stored

Function annotations are stored in `__annotations__` as a dict:

```
def fetch(url: str, timeout: float = 5.0) -> bytes:
    ...

fetch.__annotations__
# {'url': <class 'str'>, 'timeout': <class 'float'>, 'return': <class 'bytes'>}
```

Variable annotations at module or class scope are stored in the module or class `__annotations__`. Annotations inside function bodies are evaluated but **not** stored anywhere — they exist only for the type checker.

```
class Config:
    host: str
    port: int = 8080

Config.__annotations__
# {'host': <class 'str'>, 'port': <class 'int'>}
```

2.2.2 `from __future__ import annotations`

By default, annotations are evaluated eagerly at definition time. This causes problems with forward references (a class referencing itself) and with annotations that import symbols not yet defined.

```
# Without future annotations — fails at runtime
class Node:
    def children(self) -> list[Node]:  # NameError: Node not yet defined
        ...
```

The fix before Python 3.10 was to quote the annotation: `-> 'list[Node]'`. From Python 3.10+ with `from __future__ import annotations` (or natively in 3.11+), all annotations are stored as **strings** (lazy evaluation):

```python
from __future__ import annotations

class Node:
    def children(self) -> list[Node]:  # fine – stored as the string
    ↪ "list[Node]"
        ...
```

`typing.get_type_hints(obj)` resolves these strings back to types when needed, using the appropriate namespace. `__annotations__` itself returns raw strings.

Practical rule: Always use `from __future__ import annotations` in modules with any non-trivial type hints. It also improves import performance by deferring annotation evaluation.

* * *

2.3 Core Typing Constructs

2.3.1 Basic Builtins vs `typing` Aliases

From Python 3.9+, built-in collection types are directly parameterizable:

```python
# Python 3.9+
def process(items: list[int]) -> dict[str, list[int]]:
    ...

# Pre-3.9 (still works everywhere, but verbose)
from typing import List, Dict
def process(items: List[int]) -> Dict[str, List[int]]:
    ...
```

The capitalized `typing.List`, `typing.Dict`, etc. are aliases that exist purely for backward compatibility. Prefer the lowercase builtins in new code targeting 3.9+.

2.3.2 `Optional` and `Union`

`Optional[X]` is precisely `Union[X, None]`. Nothing more.

```python
from typing import Optional, Union

def find(key: str) -> Optional[str]:      # may return None
    ...

def parse(val: Union[str, int]) -> float: # accepts str or int
    ...

# Python 3.10+ — cleaner union syntax using |
def find(key: str) -> str | None:
    ...

def parse(val: str | int) -> float:
    ...
```

Design note: `Optional` return types force callers to handle `None`. This is correct when `None` is a meaningful absence. If `None` signals an error, raise an exception instead. Proliferating `Optional` through a codebase creates chains of `if x is not None` checks; consider a `Result` type or exceptions.

2.3.3 Any

`Any` is a special form that is simultaneously a subtype and supertype of every type. It is the escape hatch from the type system:

```python
from typing import Any

def legacy_function(data: Any) -> Any:
    ...
```

A value typed as `Any`:

- Can be passed where any type is expected.
- Can have any attribute accessed without error.
- Can be called with any arguments.

`Any` is contagious: operations on `Any` values return `Any`. This is by design – once you leave the type system, the checker cannot reason further. Minimize `Any` to integration boundaries with untyped libraries.

`object` is not `Any`. `object` is the actual root base class; the type checker will only permit operations defined on `object`. `Any` disables checking entirely.

2.3.4 `Union` Narrowing

The type checker tracks which branch of a union is active through control flow analysis:

```
def process(val: str | int) -> str:
    if isinstance(val, str):
        return val.upper()   # checker knows val is str here
    else:
        return str(val * 2)  # checker knows val is int here
```

This is called **type narrowing**. Supported narrowing forms:

- `isinstance(x, T)` – narrows to `T`
- `x is None` / `x is not None` – narrows `Optional[T]`
- `assert isinstance(x, T)` – narrows after the assertion
- **`TypeGuard`** – user-defined narrowing functions

```
from typing import TypeGuard

def is_str_list(val: list[object]) -> TypeGuard[list[str]]:
    return all(isinstance(x, str) for x in val)

def process(val: list[object]) -> None:
    if is_str_list(val):
        # val is narrowed to list[str] here
        print(val[0].upper())
```

2.3.5 `Literal`

Constrains a value to a specific set of literal values:

```python
from typing import Literal

def open_file(path: str, mode: Literal['r', 'w', 'a', 'rb', 'wb']) -> None:
    ...

open_file('data.txt', 'r')    # ok
open_file('data.txt', 'x')    # type error
```

Useful for discriminated unions, configuration options, and any argument where the set of valid values is small and enumerable. Prefer `Literal` over raw `str` for such parameters.

2.3.6 `Final` and `ClassVar`

```python
from typing import Final, ClassVar

MAX_CONNECTIONS: Final = 100        # cannot be reassigned
MAX_CONNECTIONS = 200               # type error

class Config:
    instance_count: ClassVar[int] = 0   # class variable, not instance
    name: str                           # instance variable
```

`Final` prevents reassignment. It does not make the object immutable – a `Final` list can still be mutated. For immutability, use `tuple`, `frozenset`, or `dataclasses.dataclass(frozen=True)`.

`ClassVar` tells the type checker that an annotation describes a class-level variable, preventing accidental assignment through an instance.

* * *

2.4 Generics

2.4.1 `TypeVar`

A `TypeVar` is a placeholder for a type that is determined at call time. It links types across a function signature:

```python
from typing import TypeVar

T = TypeVar('T')

def first(seq: list[T]) -> T:
    return seq[0]

x: int   = first([1, 2, 3])     # T is inferred as int
y: str   = first(['a', 'b'])    # T is inferred as str
z: float = first([1, 2, 3])     # type error: int is not float
```

The string name passed to `TypeVar` should match the variable name – this is a convention the type checker uses in error messages.

Constrained TypeVar – restricts T to a specific set of types:

```python
Numeric = TypeVar('Numeric', int, float, complex)

def square(x: Numeric) -> Numeric:
    return x * x
```

Bounded TypeVar – T must be a subtype of the bound:

```python
from typing import TypeVar
from collections.abc import Hashable

H = TypeVar('H', bound=Hashable)

def add_to_set(s: set[H], item: H) -> set[H]:
    return s | {item}
```

Constrained means "exactly one of these types." Bounded means "this type or any subtype."

2.4.2 Generic Classes

```python
from typing import TypeVar, Generic

T = TypeVar('T')
E = TypeVar('E', bound=Exception)

class Result(Generic[T, E]):
    """
    Explicit Result type: either a value of type T or an error of type E.
    More explicit than Optional; useful for APIs that must not raise.
    """

    def __init__(self, value: T | None = None, error: E | None = None):
        self._value = value
        self._error = error

    @classmethod
    def ok(cls, value: T) -> 'Result[T, E]':
        return cls(value=value)

    @classmethod
    def err(cls, error: E) -> 'Result[T, E]':
        return cls(error=error)

    def is_ok(self) -> bool:
        return self._error is None

    def unwrap(self) -> T:
        if self._error is not None:
            raise self._error
        return self._value  # type: ignore[return-value]

    def unwrap_or(self, default: T) -> T:
        return self._value if self.is_ok() else default
```

When subclassing a generic class, you can specialize or remain generic:

```python
class IntResult(Result[int, ValueError]):
    # Specialized: T=int, E=ValueError
    pass

class AnyResult(Result[T, Exception]):  # Still generic in T
    pass
```

2.4.3 `ParamSpec` and `Concatenate` (Python 3.10+)

`TypeVar` cannot capture an entire parameter list. `ParamSpec` fills this gap – it is essential for correctly annotating decorators:

```python
from typing import ParamSpec, Callable, TypeVar
import functools

P = ParamSpec('P')
R = TypeVar('R')

def logged(func: Callable[P, R]) -> Callable[P, R]:
    @functools.wraps(func)
    def wrapper(*args: P.args, **kwargs: P.kwargs) -> R:
        print(f"Calling {func.__name__}")
        result = func(*args, **kwargs)
        print(f"Done {func.__name__}")
        return result
    return wrapper

@logged
def fetch(url: str, timeout: float) -> bytes:
    ...

fetch('http://example.com', 5.0)   # type checker knows full signature
```

Without `ParamSpec`, the inner `wrapper` would be typed as `(*args: Any, **kwargs: Any) -> R`, losing all parameter type information.

2.4.4 `TypeVarTuple` (Python 3.11+)

Enables variadic generics – typing heterogeneous tuples of arbitrary length (used internally by `tuple`, `zip`, etc.):

```python
from typing import TypeVarTuple, Unpack

Ts = TypeVarTuple('Ts')

def broadcast(func: Callable[[Unpack[Ts]], None], *args: Unpack[Ts]) -> None:
    func(*args)
```

This is advanced and rarely needed in application code, but appears in library internals.

* * *

2.5 Structural Typing with `Protocol`

`Protocol` enables **structural subtyping** (duck typing made explicit). A class satisfies a `Protocol` if it implements the required methods and attributes, regardless of inheritance:

```
from typing import Protocol, runtime_checkable

class Closeable(Protocol):
    def close(self) -> None:
        ...

class Serializable(Protocol):
    def to_bytes(self) -> bytes:
        ...
    def from_bytes(self, data: bytes) -> None:
        ...

@runtime_checkable
class Drawable(Protocol):
    def draw(self) -> None:
        ...

class Circle:
    def draw(self) -> None:
        print("Drawing circle")

# No inheritance — structurally satisfies Drawable
def render(obj: Drawable) -> None:
    obj.draw()

render(Circle())   # type checker: ok
```

`@runtime_checkable` allows `isinstance(obj, Drawable)` at runtime, but only checks for method presence (not signatures). Without it, `Protocol` is purely a static artifact.

Protocol vs ABC:

- `Protocol` — structural; no explicit registration or inheritance required; better for functions that accept anything with a given shape.
- `ABC` — nominal; requires `register()` or explicit inheritance; better when you want to enforce a full contract via `abstractmethod`.

Protocol with attributes:

```python
class HasName(Protocol):
    name: str   # Structural: any object with a `name: str` attribute qualifies
```

* * *

2.6 `TypedDict`

A `TypedDict` defines the expected structure of a dict without converting it to a class:

```python
from typing import TypedDict, Required, NotRequired

class UserRecord(TypedDict):
    id: int
    name: str
    email: str
    role: NotRequired[str]   # optional key

def create_user(record: UserRecord) -> None:
    print(record['name'])

create_user({'id': 1, 'name': 'Alice', 'email': 'a@b.com'})   # ok
create_user({'id': 1, 'name': 'Alice'})   # type error: missing 'email'
```

`TypedDict` is useful at I/O boundaries – JSON payloads, API responses, config files – where the data is genuinely a dict and converting it to a dataclass would be overhead. It does not provide runtime validation.

Inheritance – `TypedDict` supports inheritance to compose schemas:

```python
class BaseRecord(TypedDict):
    id: int
    created_at: str

class UserRecord(BaseRecord):
    name: str
    email: str
```

* * *

2.7 `dataclass` vs `NamedTuple` vs `TypedDict`

Choosing the right tool:

	`dataclass`	`NamedTuple`	`TypedDict`
Type	Class instance	Tuple subclass	Plain dict
Mutable	Yes (default)	No	Yes
Hashable	No (unless `frozen=True` + no mutable fields)	Yes	No
Inheritance	Full	Limited	Yes
Runtime overhead	Low	Very low	None
Positional unpacking	No	Yes	No
`__slots__`	Via `slots=True` (3.10+)	Built-in	N/A
Use case	Mutable domain objects	Lightweight value objects	Dict schema at I/O boundaries

```python
from dataclasses import dataclass, field
from typing import NamedTuple

@dataclass(frozen=True, slots=True)
class Point:
    x: float
    y: float

class Coordinate(NamedTuple):
    latitude: float
    longitude: float

# NamedTuple: positional access, tuple semantics
lat, lon = Coordinate(51.5, -0.1)   # tuple unpacking
```

2.7.1 `dataclass` in Depth

```python
from dataclasses import dataclass, field, KW_ONLY

@dataclass(order=True, frozen=True, slots=True)
class Version:
    major: int
    minor: int
    patch: int

    def __str__(self) -> str:
        return f"{self.major}.{self.minor}.{self.patch}"

@dataclass
class Pipeline:
    name: str
    _: KW_ONLY                          # everything after this is keyword-only
    stages: list[str] = field(default_factory=list)
    metadata: dict[str, str] = field(default_factory=dict, repr=False)
    _id: int = field(default=0, init=False, repr=False)  # not in __init__

    def __post_init__(self):
        # Runs after __init__; use for validation and derived fields
        if not self.name:
            raise ValueError("Pipeline name cannot be empty")
        object.__setattr__(self, '_id', id(self))  # needed if frozen=True
```

`field()` parameters:

- `default` / `default_factory` – use `default_factory` for mutable defaults.
- `init=False` – exclude from `__init__`; set in `__post_init__`.
- `repr=False` – exclude from `__repr__`.
- `compare=False` – exclude from `__eq__` and ordering methods.
- `hash=None` – follows `compare` by default.

* * *

2.8 `@overload`

When a function has multiple valid signatures with different return types depending on argument types, use `@overload` to provide the checker with each signature. The implementation uses a final non-decorated definition:

```python
from typing import overload

@overload
def parse(data: str) -> dict: ...
@overload
def parse(data: bytes) -> dict: ...
@overload
def parse(data: dict) -> dict: ...

def parse(data: str | bytes | dict) -> dict:
    if isinstance(data, dict):
        return data
    if isinstance(data, bytes):
        data = data.decode()
    import json
    return json.loads(data)
```

The `@overload` variants are invisible at runtime — they are erased and only the final implementation exists. The type checker uses the overloads to resolve calls.

When to use `@overload`:

- Return type varies based on argument type.
- Combinations of optional arguments that are mutually exclusive.
- When `Union` return types would be too permissive.

* * *

2.9 Abstract Base Classes and `typing.abc`

`collections.abc` provides abstract base classes for container protocols. These interact with the type system:

```python
from collections.abc import (
    Iterable, Iterator, Generator,
    Sequence, MutableSequence,
    Mapping, MutableMapping,
    Callable, Awaitable, Coroutine,
    AsyncIterable, AsyncIterator
)
```

Prefer these over concrete types in function signatures:

```python
# BAD – overly restrictive; rejects tuples, generators, etc.
def process(items: list[int]) -> None: ...

# GOOD – accepts anything iterable
def process(items: Iterable[int]) -> None: ...

# GOOD – accepts any sequence (supports len and indexing)
def process(items: Sequence[int]) -> None: ...
```

The rule: **accept the most general type your implementation actually needs; return the most specific type your implementation actually produces.**

2.9.1 Annotating Iterators and Generators

```python
from collections.abc import Iterator, Generator

def count_up(start: int) -> Iterator[int]:
    n = start
    while True:
        yield n
        n += 1

# Generator[YieldType, SendType, ReturnType]
def accumulator() -> Generator[float, float, str]:
    total = 0.0
    while True:
        value = yield total   # yields float, receives float via send()
        if value is None:
            return f"Final total: {total}"
        total += value
```

`Iterator[T]` is equivalent to `Generator[T, None, None]`. Use `Iterator[T]` when you only yield. Use `Generator[Y, S, R]` only when `send()` or `return` values matter.

* * *

2.10 Annotating Callables

```python
from collections.abc import Callable

# Callable[[arg_types...], return_type]
def apply(func: Callable[[int, int], int], x: int, y: int) -> int:
    return func(x, y)

# Callable with no arguments
def run(task: Callable[[], None]) -> None:
    task()

# Callable with unknown signature — Callable[..., R]
def wrap(func: Callable[..., int]) -> Callable[..., int]:
    ...
```

`Callable[..., R]` means "callable returning R, any parameters." Use this when you genuinely don't care about parameter types (e.g., a retry decorator that wraps any function).

* * *

2.11 Runtime Type Checking

Type annotations do not enforce types at runtime. For runtime validation:

Option 1: Manual assertions (fine for internal code):

```python
def connect(host: str, port: int) -> None:
    assert isinstance(host, str), f"Expected str, got {type(host)}"
    assert isinstance(port, int) and 1 <= port <= 65535
```

Option 2: `dataclass` with `__post_init__` (good for domain objects):

```python
@dataclass
class Config:
    host: str
    port: int

    def __post_init__(self):
        if not isinstance(self.host, str):
            raise TypeError(f"host must be str, got {type(self.host)}")
        if not (1 <= self.port <= 65535):
            raise ValueError(f"port must be 1-65535, got {self.port}")
```

Option 3: `pydantic` (the de facto standard for API-boundary validation):

```python
from pydantic import BaseModel, Field

class Config(BaseModel):
    host: str
    port: int = Field(ge=1, le=65535)
    timeout: float = 5.0

cfg = Config(host='localhost', port='8080')  # port coerced to int
cfg = Config(host='localhost', port=99999)   # ValidationError
```

Pydantic coerces types where possible and raises `ValidationError` with detailed field-level messages. It is the correct tool for parsing and validating external data (HTTP bodies, config files, CLI args).

* * *

2.12 `mypy` Configuration and Usage Patterns

2.12.1 Key `mypy` Flags

```ini
# mypy.ini
[mypy]
python_version = 3.11
strict = True          # enables all strictness flags

# Individual flags (subset of what --strict enables)
warn_return_any = True          # warn when returning Any
warn_unused_ignores = True      # warn about unnecessary # type: ignore
disallow_untyped_defs = True    # require annotations on all functions
disallow_any_generics = True    # disallow bare List, Dict without params
check_untyped_defs = True      # type-check function bodies without annotations
no_implicit_optional = True     # Optional[X] must be explicit; X | None = ...
↪  no longer allowed as default
```

2.12.2 `# type: ignore` and `cast`

```python
from typing import cast

# Suppress a single error — use sparingly, document why
value = legacy_function()   # type: ignore[return-value]

# Inform the type checker of a type it cannot infer
result = cast(list[str], some_dynamic_function())
```

`cast(T, x)` is a no-op at runtime — it returns `x` unchanged. It is a type-checker-only assertion. Use it at well-understood boundaries where you know more than the checker. Never use it to mask a genuine type error.

2.12.3 Stubs and `py.typed`

For packages you distribute, signal that you support type checking by:

1. Including a `py.typed` marker file (PEP 561).
2. Providing inline type annotations in your source.

For untyped third-party libraries, use stub files (`.pyi`) from `typeshed` or from `types-<library>` packages on PyPI.

* * *

2.13 Common Typing Mistakes and Misconceptions

Mistake 1: Conflating `Optional[X]` with "optional parameter"

```python
# WRONG interpretation: this does NOT mean `name` is optional
def greet(name: Optional[str]) -> str:
    return f"Hello, {name}"    # mypy: name could be None

# Correct: optional parameter with a default
def greet(name: str = 'World') -> str:
    return f"Hello, {name}"
```

Mistake 2: Using mutable containers as TypeVar constraints

```python
T = TypeVar('T')

def first_or_none(seq: list[T]) -> T | None:
    return seq[0] if seq else None

# T is bound per-call; the list[T] annotation is fine.
# Problem arises if you try to mutate the list assuming a specific type.
```

Mistake 3: Annotating `self` incorrectly in classmethods

```python
from typing import Self   # Python 3.11+

class Builder:
    def set_name(self, name: str) -> Self:
        self.name = name
        return self     # Self preserves the actual subclass type

class AdvancedBuilder(Builder):
    pass

b: AdvancedBuilder = AdvancedBuilder().set_name("x")  # correctly typed
```

Without `Self`, the return type would be `Builder`, losing the subclass information.

Mistake 4: Using `List` (capital) from `typing` in new code

In Python 3.9+, `list[int]` is fully supported. `typing.List` is deprecated. Use the lowercase builtins.

Mistake 5: Thinking `isinstance` is slow

It is not. `isinstance` is a C-level operation in CPython, O(depth of MRO), and fully appropriate in hot paths. The performance concern applies to deeply nested class hierarchies, not typical user code.

* * *

2.14 Typing Patterns for Interview Code

At a staff level, interviewers expect to see type annotations used confidently. The following patterns cover the most common scenarios:

```python
from __future__ import annotations
from typing import TypeVar, Generic, Protocol, overload, Final
from collections.abc import Iterator, Callable, Iterable, Sequence
from dataclasses import dataclass, field

# 1. Annotating a generic container
T = TypeVar('T')

@dataclass
class Stack(Generic[T]):
    _items: list[T] = field(default_factory=list)

    def push(self, item: T) -> None:
        self._items.append(item)

    def pop(self) -> T:
        if not self._items:
            raise IndexError("pop from empty stack")
        return self._items.pop()

    def peek(self) -> T | None:
        return self._items[-1] if self._items else None

    def __len__(self) -> int:
        return len(self._items)

    def __iter__(self) -> Iterator[T]:
        return iter(reversed(self._items))

# 2. Protocol for dependency injection
class HtmlParser(Protocol):
```

```python
    def get_urls(self, url: str) -> list[str]: ...

# 3. TypedDict for structured external data
from typing import TypedDict

class CrawlResult(TypedDict):
    url: str
    status: int
    links: list[str]
    error: str | None

# 4. Overload for multi-signature function
@overload
def load_config(path: str) -> dict[str, str]: ...
@overload
def load_config(path: None) -> None: ...

def load_config(path: str | None) -> dict[str, str] | None:
    if path is None:
        return None
    with open(path) as f:
        import json
        return json.load(f)

# 5. Callable with ParamSpec for decorators
from typing import ParamSpec
P = ParamSpec('P')
R = TypeVar('R')

def retry(max_attempts: int) -> Callable[[Callable[P, R]], Callable[P, R]]:
    def decorator(func: Callable[P, R]) -> Callable[P, R]:
        import functools
        @functools.wraps(func)
        def wrapper(*args: P.args, **kwargs: P.kwargs) -> R:
            for attempt in range(max_attempts):
                try:
                    return func(*args, **kwargs)
                except Exception:
                    if attempt == max_attempts - 1:
                        raise
        return wrapper
    return decorator
```

* * *

Summary

Construct	Purpose	When to use
`Optional[X]` / `X | None`	Nullable value	Return value may be absent
`Union[A, B]` / `A | B`	Multiple valid types	Arguments accepting heterogeneous types
`Any`	Opt out of type checking	Integration with untyped code
`TypeVar`	Generic type parameter	Linking arg/return types
`Generic[T]`	Generic class	Reusable typed containers
`Protocol`	Structural interface	Duck-typed dependencies
`TypedDict`	Dict with shape	JSON / config at boundaries
`dataclass`	Typed mutable object	Domain entities
`NamedTuple`	Typed immutable tuple	Lightweight value objects
`Literal`	Specific value set	Enum-like string params
`Final`	Non-reassignable	Constants
`ClassVar`	Class-level variable	Distinguishing class vs instance
`@overload`	Multiple signatures	Conditional return types
`ParamSpec`	Capture param list	Decorators preserving signatures
`Self`	Return subclass type	Fluent/builder patterns

* * *

Chapter 3 — Functional Programming: Comprehensions, `functools`, `itertools`

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3.1 What "Functional" Means in Python

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