UEE1303
Objective-Oriented Programming

C++_Lecture 12:

Polymorphism –

Virtual Functions and Abstract Base Class

C: How to Program 8th ed.

Agenda

- Concepts of Polymorphism (Chapter 20.1-20.3)
  - differences between static and dynamic bindings
  - virtual functions for run-time polymorphism
- Abstract base classes and Pure virtual functions (Chapter 20.5)
  - Case Study: Payroll System (Chapter 20.6)
- Inner Workings of Virtual Functions (Chapter 20.7)
- Extended Type Compatibility (Chapter 20.8)
- The importance of virtual destructors (Chapter 20.3)

Polymorphism

- Polymorphism is one of three keys in OOP and supports
  - *function overloading* and *operator overloading* at *compiler* time
  - *function overriding* at *run-time*

  ⇨ associate many meanings to one function
- Run-time polymorphism
  - enable programmers to design a common interface that can be used on different but related objects
  - reduce complexity and development time

Example for Polymorphism

```
class CPoint   //base class: class CPoint
{
    double x, y;
public:
   CPoint(double a = 0, double b = 0):
           x(a), y(b) {}
   void SetPoint(double a=0, double b=0) {
        x = a; y = b;                             }
   double GetX() const { return x; }
   double GetY() const { return y; }
   friend ostream & operator << (ostream &,
                      const CPoint&);
   string ToString() const {
        return "Cpoint";               }
};
```

Example for Polymorphism (cont.)

```
class CRect: public CPoint
{   //add new private data members
    double lg, wd;
public:   //add new member functions
    CRect(double a, double b,
          double c, double d) : lg(c),wd(d)
              { SetPoint(a, b); }
    void SetRect(double a=0, double b=0
                 double c=0, double d=0) {
         SetPoint(a, b); lg = c; wd = d;   }
    double GetL() const { return lg; }
    double GetW() const { return wd; }
    double Area() const { return lg*wd; }
    friend ostream & operator << (ostream &,
                        const CRect &);
    string ToString() const {
        return "Crect";                  }   };
```

Example for Polymorphism (cont.)

```
ostream & operator << (ostream & out,
             const CPoint& p) {
    out << p.x << " " << p.y;
    return out;
}
ostream & operator << (ostream & out,
             const CRect& p) {
    out << p.GetX() << " " << p.GetY()
        << " area " << p.Area();
    return out;
}
```

Example for Polymorphism (cont.)

```
int main()
{
    CRect cr1(2,3,20,10);
    cout << "old: " << cr1 << endl;
    cr1.SetRect(5,5,9,7);
    cout << "new: " << cr1 << endl;
    CPoint &pRf = cr1;
    cout << "pRf: " << pRf << endl;

    return 0;
}
```

```
old: 2 3 area 200
new: 5 5 area 63
pRef: 5 5
```

Another Example for Polymorphism

```
class CCuboid : public CRect {
protected:
    double ht; //ht for height
public:
    CCuboid(double a, double b,
            double c, double d, double e):
        CRect(a, b, c, d) { ht = e; }
    void SetHeight(double d = 1.0){ ht = d; }
    void GetHeight() const { return ht;   }
    double Area() const {
        return (2*CRect::Area()+2*GetL()*ht
               +2*GetW()*ht);              }
    friend ostream & operator << (ostream &,
                    const CCuboid &);
    string ToString() const {
        return "Ccuboid";             }
};
```

Another Example for Polymorphism (cont.)

```
ostream & operator << (ostream & out,
          const CCuboid& p) {
    out << p.GetX() << " " << p.GetY() <<
  " surface " << p.Area(); return out;}
```

```
int main()
{
    CCuboid cu1(2,3,20,10,5);
    cout << "old: " << cu1 << endl;
    cu1.SetRect(1,1,8,6);
    cout << "new: " << cu1 << endl;
    CPoint &pRef = cu1;
    cout << "pRef: " << pRef << endl;
    CRect &rRef = cu1;
    cout << "rRef: " << rRef << endl;
    return 0;
}
```

Static vs. Dynamic Bindings

- Binding
  - compiler reserves a space in memory for all user-defined functions and keeps track of memory address for each function
  - a function name is bound with function address ⇨ the starting memory location for the function code
- Static binding (a.k.a. *early binding*)
  - Compiler binds all function calls to the addresses of function code at compile-time
- Dynamic binding (a.k.a. *late binding*)
  - function calls are resolved at run-time
  - order of function calls depends on the action taken by the user

Realizing Polymorphism

- Compile-time polymorphism
  - apply static binding
  - advantage of fast speed
  - realized by function overloading and operator overloading
- Run-time polymorphism
  - apply dynamic binding
  - advantage of enhanced flexibility
  - realized by inheritance and virtual functions
- In C++, redefining a virtual function in a derived class is called overriding a function

```
virtual ⟨datatype⟩ ⟨fname⟩ (⟨para_list⟩);
```

Example for Polymorphism (w/o Virtual)

- Given class `CPoint`, `CRect`, and `CCuboid`

```
void DisplayObject(const CPoint & p) {
    cout << p.ToString() << endl;                }
```

```
int main() {
    CPoint o1(5,7);
    CRect o2(2,4,5,7);
    CCuboid o3(1,3,5,7,9);
    DisplayObject(o1);
    DisplayObject(o2);
    DisplayObject(o3);
    return 0;
}
```

```
CPoint
CPoint
CPoint
```

Example for Polymorphism (w/ Virtual)

```
virtual string ToString() const { ... }
```

```
void DisplayObject(const CPoint * p) {
    cout << p->ToString() << endl;        }
```

```
int main() {
    CPoint o1(5,7);
    CRect o2(2,4,5,7);
    CCuboid o3(1,3,5,7,9);
    DisplayObject(&o1);
    DisplayObject(&o2);
    DisplayObject(&o3);
    return 0;
}
```

```
CPoint
CRect
CCuboid
```

Virtual Functions

- Casting between the base class and the derived class
  - can assign a derived-class object to a base-class object
  - can copy the address of a derived-class object to a pointer of a base-class object
  - a derived-class object can be a reference to base-class object

  ⇨ can only access members in the base class, not members in the derived class
- Virtual functions makes that a pointer or reference of a base-class member can be applied onto derived-class members

Virtual Functions (cont.)

- Virtual functions tell the compiler
  - don't know how function is implemented
  - wait until used in program
  - get implementation from object instance
  - call dynamic (late) binding
- If class `C1`, `C2`, … are derived from `C0` which have a virtual function `f()` (`public` or `protected`)
  - `f()` can be redefined in `C1`, `C2`, and etc.
  - call by the base-class object or pointer to the base-class object
  - decide which `f()` to call during run-time

More on Virtual Functions

- If a function `f()` in the base class is virtual, then all `f()`'s in the derived classes are virtual
  - all redefined `f()`'s in the derived class `C1`, `C2`, and etc. have the same prototype

  ⇨ overriding ≠ overloading
  - a virtual function must be a member function of a class ⇨ cannot be *global*, *static* or *friend*
  - *destructors* can be virtual but constructors cannot be virtual
- Major disadvantage: more storage overhead + running slower ⇨ should be used if not necessary

Example of Virtual Functions

```
class B0 {
public: void ShowFun() { //not virtual
        cout << "B0::ShowFun()" << endl; }
};
class C0 : public B0 {
public: virtual void ShowFun() { //virtual
          cout << "C0::ShowFun()" << endl; }
};
class C1 : public C0 {
public: void ShowFun() { //virtual
        cout << "C1::ShowFun()" << endl; }
};
class C2 : public C1 {
public: void ShowFun() { //virtual
        cout << "C2::ShowFun()" << endl; }
};
```

Example of Virtual Functions (cont.)

```
void FunPtr(C0 *ptr) {
    ptr->ShowFun();
}
```

```
//in main()
    B0 w, *p; C0 x, *q;
    C1 y; C2 z;
    p = &w; p->ShowFun();
    p = &y; p->ShowFun(); //what happen??
    q = &x; FunPtr(q);
    q = &y; FunPtr(q);
    q = &z; FunPtr(q);
```

```
B0::ShowFun()
B0::ShowFun()
C0::ShowFun()
C1::ShowFun()
C2::ShowFun()
```

More Example of Virtual Functions

```
class A {
public: virtual void ShowFun() { //virtual
        cout << "A::ShowFun()" << endl; } };
class C : public A {
public: void ShowFun(int i) { //not virtual
        cout << "C::ShowFun()" << endl; } };
```

```
//in main()
    C c;
    A *pa = &c, &ra = c, a = c;
    a.ShowFun();
    pa->ShowFun();
    ra.ShowFun();
```

```
A::ShowFun()
A::ShowFun()
A::ShowFun()
```

More Example of Virtual Functions

```
class B {
public: virtual void ShowFun(char c) {
        cout << "B::ShowFun()" << endl; } };
class D : public B {
public: void ShowFun(int i) { //not virtual
        cout << "D::ShowFun()" << endl; } };
```

```
//in main()
    D d;
    B *pb = &d, &rb = d, b = d;
    b.ShowFun(0);
    pb->ShowFun(0);
    rb.ShowFun(0);
```

```
B::ShowFun()
B::ShowFun()
B::ShowFun()
```

More Example of Virtual Functions

```
class B { public:
    void f() { cout << "Bf "; }
    virtual void g(){ cout << "Bg "; }
    void h() { g(); f(); }
    virtual void m(){ g();  f(); }
};
class D : public B { public:
    void f() { cout << "Df "; }
    void g() { cout << "Dg "; }
    void h() { f(); g(); }
};
```

```
//in main()
    D d; B *pB = &d;
    pB->f(); pB->g(); pB->h(); pB->m();
```

```
Bf Dg Dg Bf Dg Bf
```

Virtual Destructors

- If a base-class pointer to derived-class object is deleted, the base-class destructor will act on such object ⇨ what's wrong?

```
CBase *pB = new CDerived;
...
delete pB;
```

  - deletion may not be through
  - pointer to `CDerived` object but not free `CDerived` members
- Good to always have base-class destructors as virtual destructors
  - then appropriate destructors will be called

Example of Virtual Destructors

```
class B { public:
    ~B() { cout << "B::~B()\n";}
};
class D : public B {
    int * iary;
public:
    D(int i) { iary = new int [i]; }
    ~D() {
        delete iary;
        cout << "D::~D()\n";  }
};
```

```
//in main()
    B *pB = new D(10);
    delete pB;
```

```
B::~B()
```

Example of Virtual Destructors

```
class B { public:
    virtual ~B() { cout << "B::~B()\n";}
};
class D : public B {
    int * iary;
public:
    D(int i) { iary = new int [i]; }
    ~D() {
        delete iary;
        cout << "D::~D()\n";  }
};
```

```
//in main()
    B *pB = new D(10);
    delete pB;
```

```
D::~D()
B::~B()
```

Pure Virtual Functions

- Base class might not have meaningful definition for some of its members!
  - only for other classes to derive from
- Recall class `CPoint`
  - all other figures are objects of derived classes
  - rectangles, circles, triangles, etc.
  - class `CPoint` has no idea how to calculate area ⇨ a pure virtual function

```
virtual void Area()=0;
```

Abstract Base Classes

- Pure virtual functions require no definition
  - force each derived classes to define its own version
- Class with one ore more pure virtual functions ⇨ *abstract base class*
  - can only be used as base class
  - no objects can ever be created from it because it doesn't include complete definitions of all its members
- If one derived class fails to define all pure virtual functions, then
  - also an abstract base class

Example for Abstract Base Class

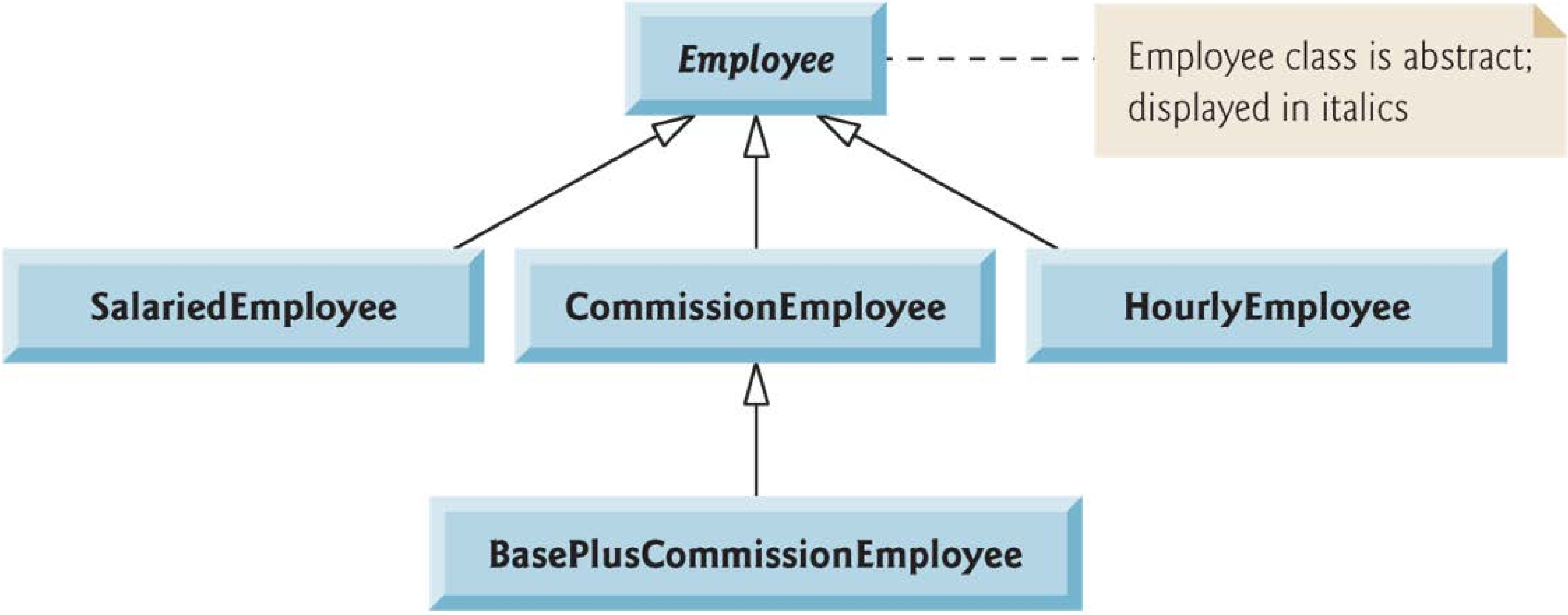
```
class CFig {
protected:
    double x, y;
public:
    void SetDim(double a=0, double b=0) {
        x = a; y = b;                              }
    virtual void Area()=0; //pure virtual!
};
class CRec: public CFig {
public: void Area(int i) {
            cout<< "Rec:" << x*y << "\n"; }
};
class CTri: public CFig {
public: void Area() {
            cout<< "Tri:" << x*y/2 << "\n";}
};
```

Example for Abstract Base Class (cont.)

```
int main() {
    CFig *pF;
    CFig  f1; //what happen?
    CRec  r2; //what happen?
    CTri  t3;
    t3.SetDim(7,5);
    pF = &t3;
    pF->Area();
    CFig &rF = t3;
    rF.SetDim(9,8);
    rF.Area();
    return 0;
}
```

```
Tri:17.5
Tri:36
```

Case Study: Payroll System



Case Study: Payroll System (cont.)

	earnings	print
Employee	= 0	*firstName lastName* social security number: *SSN*
Salaried-Employee	weeklySalary	salaried employee: *firstName lastName* social security number: *SSN* weekly salary: *weeklysalary*
Hourly-Employee	*If hours <= 40* wage * hours *If hours > 40* (40 * wage) + ((hours - 40) * wage * 1.5)	hourly employee: *firstName lastName* social security number: *SSN* hourly wage: *wage*; hours worked: *hours*
Commission-Employee	commissionRate * grossSales	commission employee: *firstName lastName* social security number: *SSN* gross sales: *grossSales*; commission rate: *commissionRate*
BasePlus-Commission-Employee	baseSalary + (commissionRate * grossSales)	base salaried commission employee: *firstName lastName* social security number: *SSN* gross sales: *grossSales*; commission rate: *commissionRate*; base salary: *baseSalary*

Employee.h

```
// Fig. 21.13: Employee.h
// Employee abstract base class
#ifndef EMPLOYEE_H
#define EMPLOYEE_H
#include <string>
using namespace std;
class Employee
{
public:
    Employee (const string &, const string &, const string
&);
    void setFirstName(const string &); // set first name
    string getFirstName() const;
    void setLastName(const string &); // set last name
    string getLastName() const;
    void setSocialSecurityNumber(const string &); // set
SSN
    string getSocialSecurityNumber() const;
```

Employee.h (cont.)

```
    // pure virtual function makes Employee abstract base
class
    virtual double earnings() const = 0; // pure virtual
    virtual void print() const; // virtual
private:
    string firstName;
    string lastName;
    string socialSecurityNumber;
}; // end class Employee
#endif
```

SalariedEmployee.h

```
// Fig. 21.15: SalariedEmployee.h
// SalariedEmployee class derived from Employee
#ifndef SALARIED_H
#define SALARIED_H
#include "Employee.h"
class SalariedEmployee : public Employee
{
public:
    SalariedEmployee (const string &, const string &,
const string &, double = 0.0);
    void setWeelkySalary(double); // set weekly salary
    double getWeeklySalary() const;
    // keyword virtual signals intent to override
    virtual double earnings() const; // calculate earnings
    virtual void print() const;
private:
    double weeklySalary;
}; // end class SalariedEmployee
#endif
```

Extended Type Compatibility

- Given: `CDerived` is derived class `CBase`
  - `CDerived` objects can be assigned to objects of type `CBase`
  - But NOT the other way!
- Example:

```
class Pet {
public:
    string name;
    virtual void print() const;       };

class Dog : public Pet {
public:
    string breed;
    virtual void print() const;       };
```

Classes `Pet` and `Dog`

- Now given declarations:

```
Dog vdog;
Pet vpet;
```

  - Member variables `name` and `breed` are public ⇨ for example, not typical

- Anything that “is a” dog “is a” pet:

```
vdog.name = "Tiny";
vdog.breed = "Maltese";
vpet = vdog;
```

  - above are allowable
  - a pet “is not a” dog (not necessarily)

Slicing Problem

- The value assigned to variable `vpet` loses its `breed` field
  - ex: `cout << vpet.breed;` ⇨ produce ERROR!
  - called slicing problem
- Might seem appropriate
  - `Dog` was moved to `Pet` variable, so it should be treated like a `Pet`
  - therefore not have `Dog` properties
  - make for interesting philosophic debate

Example for Slicing Problem

```
class Pet {
public:
    string name;
    virtual void print() const;      };

class Dog : public Pet {
public:
    string breed;
    virtual void print() const;      };
```

```
Pet *ppet;
Dog *pdog;
pdog = new Dog;
pdog->name = "Tiny";
pdog->breed = "Maltese";
ppet = pdog;
cout << ppet->breed; //what happens?
//cannot access breed => slicing problem
```

Example of Casting

- Consider

```
Pet vpet; //base-class object
Dog vdog; //derived-class object
vdog = static_cast<Dog>(vpet);  //Illigal
```

- Cannot (down)cast a pet object to be a dog object, but

```
vpet = vdog;   // Legal!
vpet = static_cast<Pet>(vdog); //Legal!
```

- Upcasting is **OK** and safe
  - from descendant type to ancestor type
  - but not the other way (downcasting)

Downcasting & `dynamic_cast`

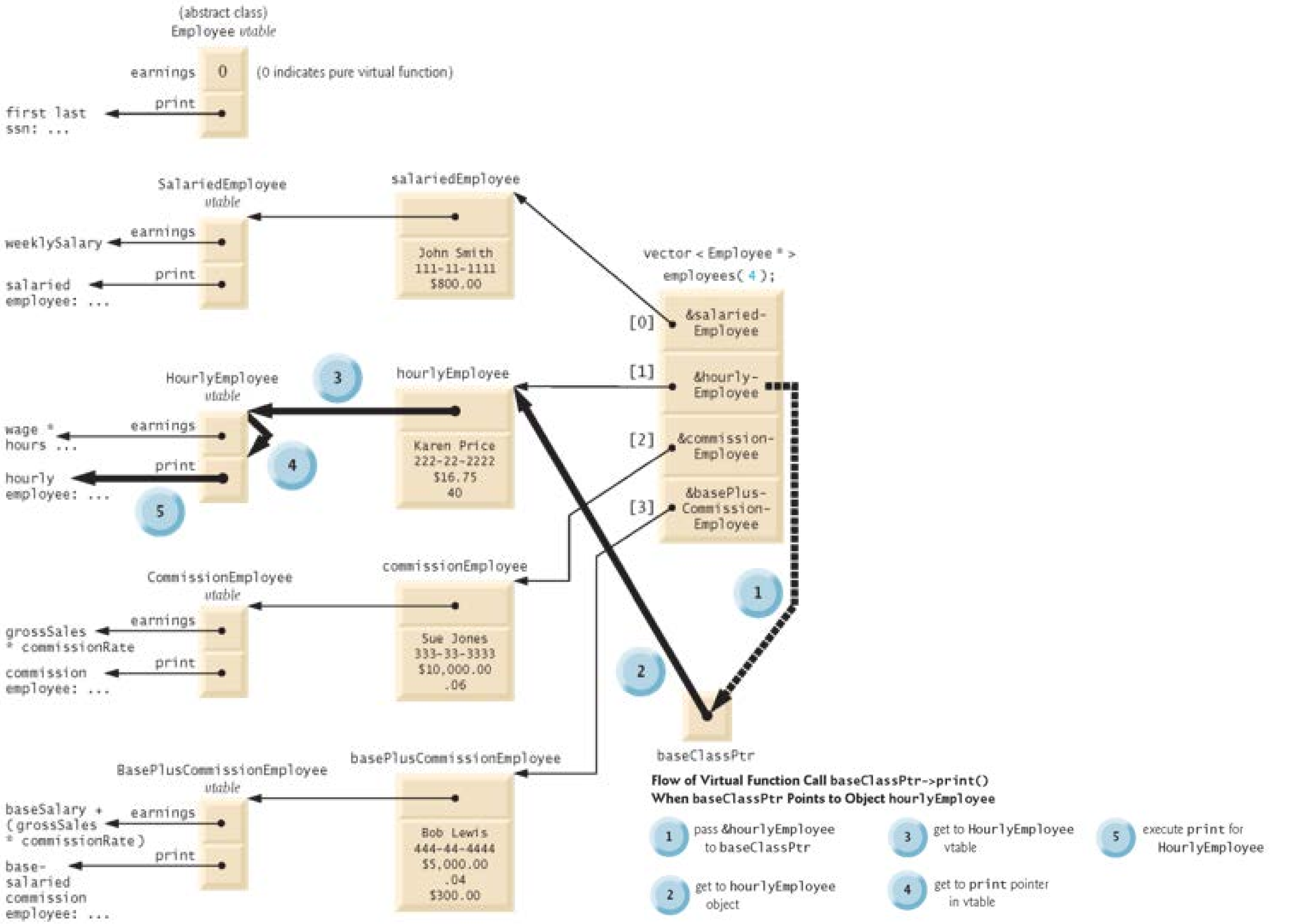
- Downcasting is dangerous! (self-study)
  - casting from the ancestor type to the descendant type
  - assume more *additional* information
  - can be done with `dynamic_cast`

```
Pet *ppet;
ppet = new Dog;
Dog *pdog = dynamic_cast<Dog*>(ppet);
```

  - Legal, but dangerous
- Downcasting rarely done due to pitfalls
  - must track all information to be added
  - all member functions must be *virtual*

Inner Workings of Virtual Functions

- Don't need to know how to use it!
  - principle of information hiding
- Virtual function table
  - compiler creates it
  - has pointers for each virtual member function
  - points to location of correct code for that function
- Objects of such classes also have a pointer
  - point to virtual function table


(abstract class)
Employee vtable
earnings
0
(0 indicates pure virtual function)
print
first last
ssn: ...
SalariedEmployee
vtable
salariedEmployee
earnings
weeklySalary
print
salaried
employee: ...
John Smith
111-11-1111
$800.00
vector < Employee * >
employees(4);
[0]
&salaried-
Employee
[1]
&hourly-
Employee
[2]
&commission-
Employee
[3]
&basePlus-
Commission-
Employee
HourlyEmployee
vtable
3
hourlyEmployee
earnings
wage *
hours ...
4
print
hourly
employee: ...
5
Karen Price
222-22-2222
$16.75
40
1
2
CommissionEmployee
vtable
commissionEmployee
earnings
grossSales
* commissionRate
print
commission
employee: ...
Sue Jones
333-33-3333
$10,000.00
.06
BasePlusCommissionEmployee
vtable
basePlusCommissionEmployee
earnings
baseSalary +
(grossSales
* commissionRate)
print
base-
salaried
commission
employee: ...
Bob Lewis
444-44-4444
$5,000.00
.04
$300.00
baseClassPtr
Flow of Virtual Function Call baseClassPtr->print()
When baseClassPtr Points to Object hourlyEmployee
1 pass &hourlyEmployee to baseClassPtr
2 get to hourlyEmployee object
3 get to HourlyEmployee vtable
4 get to print pointer in vtable
5 execute print for HourlyEmployee

Summary

- Late binding delays decision of which member function is called until run-time
  - in C++, virtual functions use late binding

- Pure virtual functions have no definition
  - classes with at least one are abstract
  - no objects can be created from abstract class
  - used strictly as base for others to derive

Summary (cont.)

- Derived class objects can be assigned to base class objects
  - base-class members are lost ⇨ slicing problem
- Pointer assignments and dynamic objects
  - allow "fix" to slicing problem
- Make all destructors virtual
  - good programming practice
  - Ensure memory correctly de-allocated

References

- Paul Deitel and Harvey Deitel, “C How to Program” Sixth Edition
  - Chapter 21
- Paul Deitel and Harvey Deitel, “C++ How to Program (late objects version)” Seventh Edition
  - Chapter 13
- W. Savitch, “Absolute C++,” Fourth Edition
  - Chapter 15