

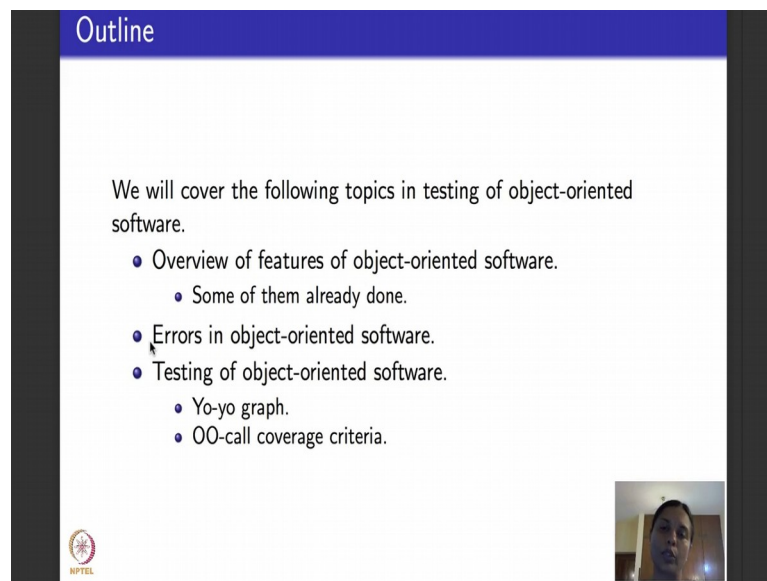
Software testing
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Lecture - 48
Testing of Object-Oriented Applications

Hello again, we continue with week 10's lecture. Last three lectures we discussed about if I have a web application and I want to test for functionality at the system level where the client software and the server software is put together, what are the properties and techniques we can test for web applications.

Now moving on, what I would like to begin with this lecture is testing of object oriented applications. If you see object oriented programming languages, the most classical of them being Java or even C++ are extensively used and even, in fact, Android code could also be object oriented.

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The slide is titled "Outline" in a blue header. The main content area is white and contains the following text:

We will cover the following topics in testing of object-oriented software.

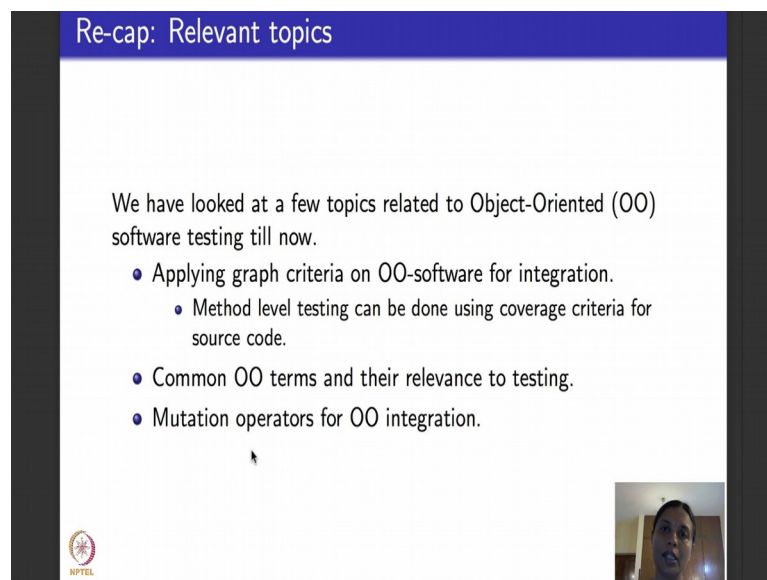
- Overview of features of object-oriented software.
 - Some of them already done.
- Errors in object-oriented software.
- Testing of object-oriented software.
 - Yo-yo graph.
 - OO-call coverage criteria.

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So, we will see generic testing of object oriented applications over the next few lectures beginning with today. So, what is the outline that we are going to cover in the next few lectures? We will cover the following topics I will begin with giving overviews of features of object oriented software.

If you remember when we did mutation testing, I had already given you several features of object oriented software. If you missed that I urge you to go back and look at those lectures because I will not be recapping them in these lectures following which we will discuss about errors or anomalies that arise specific to features of object oriented software especially inheritance and polymorphism. And then we will discuss testing of object oriented software very unique graph models which are labeled Yo-Yo graph after the toy Yo-Yo, arise when testing object oriented software. So, we will see that model today and we will also define several call coverage criteria specific to object oriented software.

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Re-cap: Relevant topics

We have looked at a few topics related to Object-Oriented (OO) software testing till now.

- Applying graph criteria on OO-software for integration.
 - Method level testing can be done using coverage criteria for source code.
- Common OO terms and their relevance to testing.
- Mutation operators for OO integration.

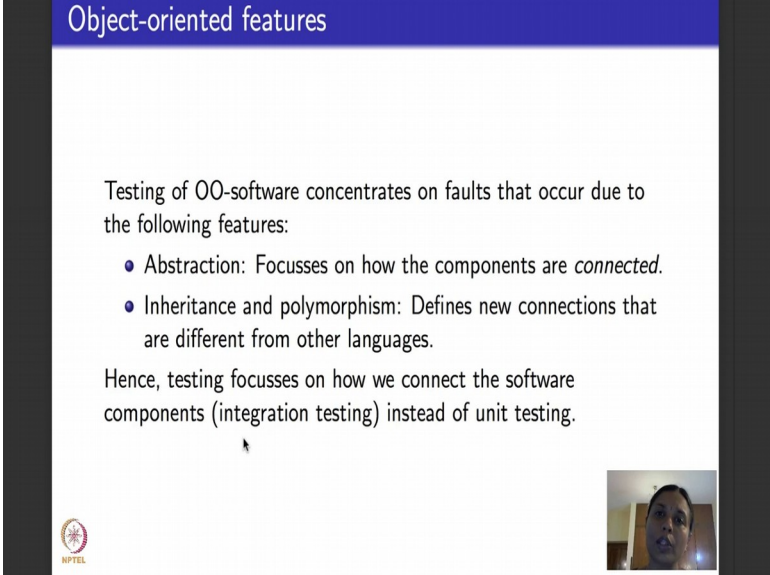
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So, what have we done till now in all the lectures that we have covered when it comes to object oriented software. So, if you remember when we did integration testing, we specifically saw how to apply graph based coverage for object oriented software integration.

And in that, if you consider unit testing which means testing inside each method that can be done by using any traditional testing that we saw--- like graph based testing, logic based testing, all of them apply equally well to unit test. And then we also I told you we saw common object oriented terms and introduced them as they relevant to testing. To reiterate it was not meant to be a thorough introduction to object oriented programming, but only just a list of features as we would needed for testing and when we did mutation

operators, specifically integration testing mutation operators we saw operators for object oriented integration also.

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The slide is titled "Object-oriented features" in a blue header. The main content area is white and contains the following text:

Testing of OO-software concentrates on faults that occur due to the following features:

- Abstraction: Focuses on how the components are *connected*.
- Inheritance and polymorphism: Defines new connections that are different from other languages.

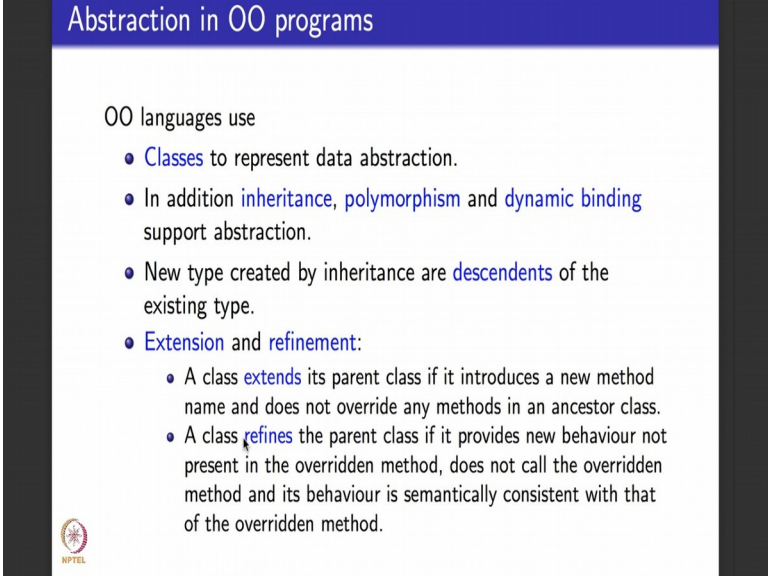
Hence, testing focusses on how we connect the software components (integration testing) instead of unit testing.

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So, now what I will do is I will introduce and recap some of the relevant object oriented features that we will need for this lecture in the next couple of lectures. So, what do object oriented software do? One of the central features that object oriented programming provides is that of abstraction. So, abstraction let us you abstract the kind of information that you want typically as classes and you focus on how the components are connected, that various abstract components are connected. We also discussed features like inheritance and polymorphism when I introduced them last time. They basically define new connections that these abstractions offer and these are typically not found in of non object oriented languages.

So, our module as we will see for object oriented programming please remember we will not focus on testing inside a method what we are instead going to focus on is integration testing. I will show you the four levels of object oriented testing and also show you which part that we are going to focus on.

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The slide has a blue header with the text "Abstraction in OO programs". The main content is on a white background with a black border. It lists concepts used in OO languages. A small NPTEL logo is in the bottom left corner.

Abstraction in OO programs

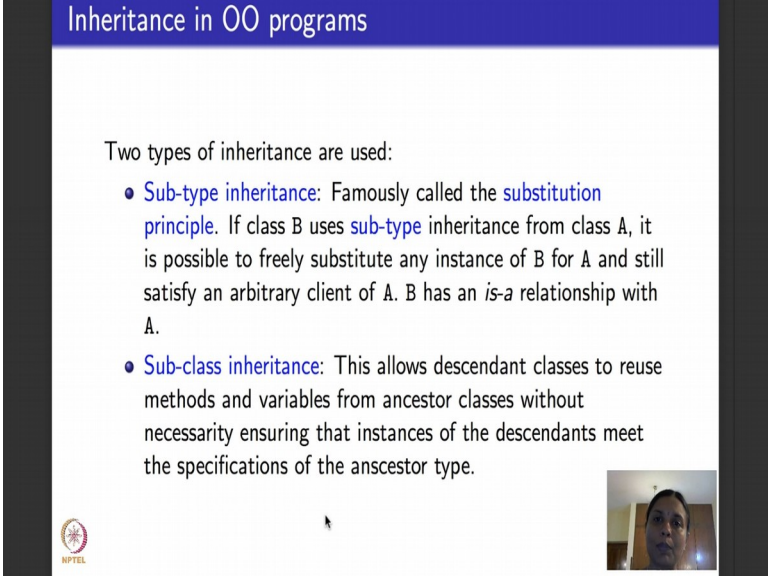
OO languages use

- **Classes** to represent data abstraction.
- In addition **inheritance**, **polymorphism** and **dynamic binding** support abstraction.
- New type created by inheritance are **descendents** of the existing type.
- **Extension** and **refinement**:
 - A class **extends** its parent class if it introduces a new method name and does not override any methods in an ancestor class.
 - A class **refines** the parent class if it provides new behaviour not present in the overridden method, does not call the overridden method and its behaviour is semantically consistent with that of the overridden method.

Before we move on what is abstraction and object oriented programs look like? The central entity in abstraction are that of classes, classes represent data abstraction. In addition to classes we have features like inheritance, polymorphism, dynamic binding, that also support abstractions, and how is a new type created? New type could be created by inheritance and as the word says, if it is a new type created by inheritance then whatever is created is called a descendant of the existing type of abstraction. Now there could be two kinds of new types that could be created. You could have extension or you could have refinement.

So, what is an extension? We say a particular class extends its parent class if it introduces a new method name and it does not override any method from its parent or ancestor. A particular class, on the other hand, refines a parent class if it provides new behavior that is not present in the overridden method and it also does not call the overridden method and in now along with that its behavior is semantically consistent with that of overridden method.

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The slide is titled "Inheritance in OO programs" in a blue header. Below the title, it states "Two types of inheritance are used:". There are two bullet points: 1. "Sub-type inheritance: Famously called the substitution principle. If class B uses sub-type inheritance from class A, it is possible to freely substitute any instance of B for A and still satisfy an arbitrary client of A. B has an is-a relationship with A." 2. "Sub-class inheritance: This allows descendant classes to reuse methods and variables from ancestor classes without necessarily ensuring that instances of the descendants meet the specifications of the ancestor type." In the bottom right corner, there is a small video feed of a person speaking. In the bottom left corner, there is a small NPTEL logo.

Inheritance in OO programs

Two types of inheritance are used:

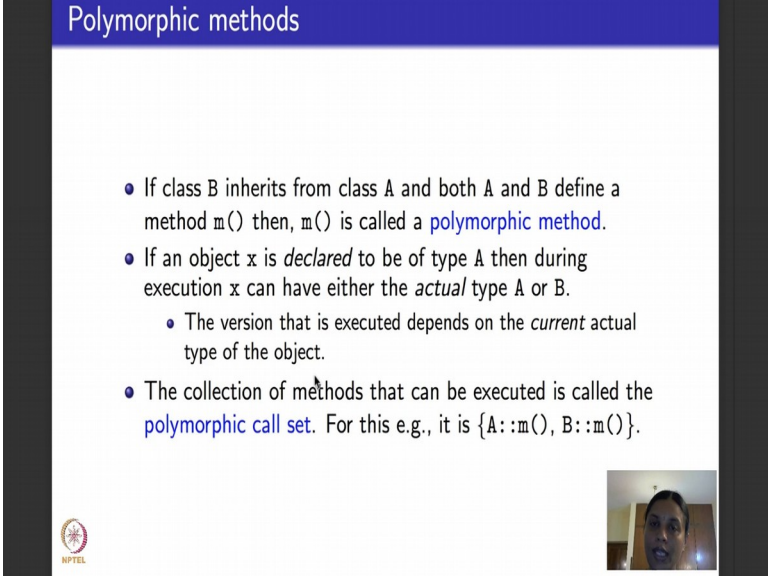
- **Sub-type inheritance:** Famously called the **substitution principle**. If class B uses **sub-type** inheritance from class A, it is possible to freely substitute any instance of B for A and still satisfy an arbitrary client of A. B has an *is-a* relationship with A.
- **Sub-class inheritance:** This allows descendant classes to reuse methods and variables from ancestor classes without necessarily ensuring that instances of the descendants meet the specifications of the ancestor type.

Moving on we considered two types of inheritance. Please remember all the terminologies that I am defining currently now is irrespective of the specific object oriented programming language that I use. These are generic object oriented features that. We will consider towards testing of object oriented software. So, there are two kinds of inheritance one is called the subtype inheritance, this is famously called substitution principle invented by this computer scientist called Barbara Liskov, who subsequently won the Turing award for this.

So, we say a particular class, let us say class B, uses subtype inheritance from class A, if it is possible to freely substitute any instance of B for a and still satisfy an arbitrary client for class A. So, we say B because it can be freely substituted for any A. So, we say B has what is called “is a relationship”. What do we mean by that? That any instance of class B is also an instance of class A. So, B can be freely substituted for class A. The next kind of inheritance is what is called subclass inheritance, where descendant classes reuse methods and variables from ancestor classes without necessarily ensuring that the instance of the descendant classes meet the specifications of the ancestor class.

So, two kinds of inheritance: subtype and subclass. Subtype means B is also class A, can be freely used like that, subclass means descendant classes reuse methods and variables, but they do not have to meet all the specifications of a parent class.


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Polymorphic methods

- If class B inherits from class A and both A and B define a method $m()$ then, $m()$ is called a **polymorphic method**.
- If an object x is *declared* to be of type A then during execution x can have either the *actual* type A or B.
 - The version that is executed depends on the *current* actual type of the object.
- The collection of methods that can be executed is called the **polymorphic call set**. For this e.g., it is $\{A::m(), B::m()\}$.

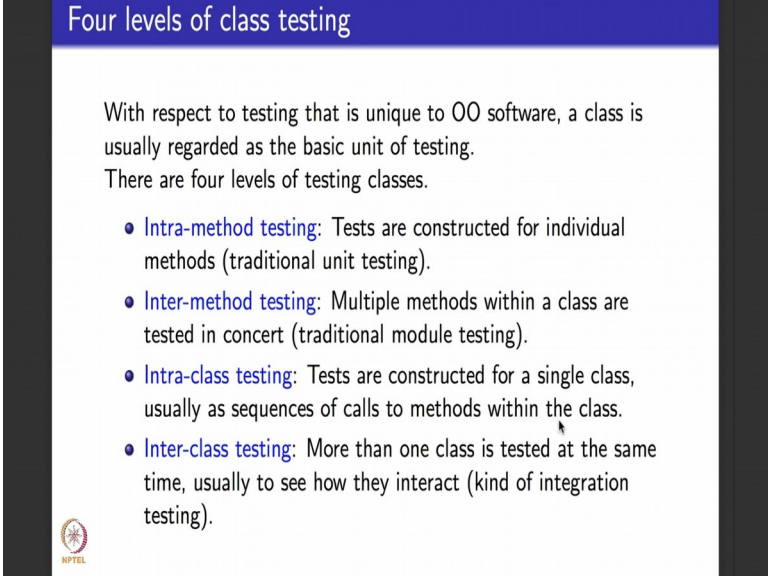
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Now, just to recap what polymorphic methods are, because we would need this extensively today. We have already done this in one of the lectures, but I will recap it once again. So, consider two classes A and B and let us say class B inherits from class A and let us say both the classes A and B define a particular method m . So, m is defined in A and m is also defined in B and in addition B inherits from A. Such a method m in object oriented programming is called polymorphic method.

So, what happens now with polymorphic methods? Suppose there is an object X that is declared to be of type A then during execution, because B inherits from A the actual type can be A or B. Whichever the type that takes is completely dependent on the execution that happens right. This collection of methods which are polymorphic that can be executed when a particular object of a particular type is called is called a polymorphic call set. For example, in this case where there are two classes A and B and both define a method m , the polymorphic call set is $A::m()$, as it occurs in class A and m as it occurs in class B.


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Four levels of class testing

With respect to testing that is unique to OO software, a class is usually regarded as the basic unit of testing. There are four levels of testing classes.

- **Intra-method testing:** Tests are constructed for individual methods (traditional unit testing).
- **Inter-method testing:** Multiple methods within a class are tested in concert (traditional module testing).
- **Intra-class testing:** Tests are constructed for a single class, usually as sequences of calls to methods within the class.
- **Inter-class testing:** More than one class is tested at the same time, usually to see how they interact (kind of integration testing).



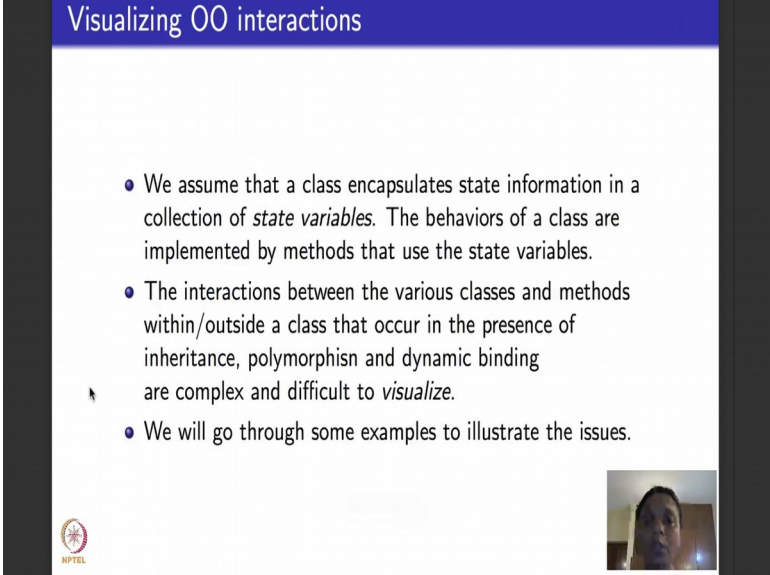
So, when while testing object oriented software we consider four levels of testing. We consider class as the basic unit of testing not a method as I told you when we consider a method as a basic unit of testing you could use any of the earlier coverage criteria that we learnt graphs, logic, mutation testing to be able to do method level testing. For us now focuses on a class level testing. So, with reference to class level testing for object oriented software, they could be four categories of testing. The first most elementary category involves intra method testing; that means, testing a particular method.

As I just told you use any applicable condition that we have learnt till now to test whether the method behaves as per its functionality, this is traditional unit testing. Moving up one level up from a method the next level of testing is inter method testing where interactions between methods are tested. This is traditional module level integration testing we have checked this when we did design integration testing based on graphs. In fact, we saw specific object oriented integration operators even for mutation.

The next is intra class testing that is testing within a class, what happens here? Tests are conducted for a single class that fixed to be tested at a particular point in time usually the tests are a sequence of calls to methods within a class. So, this class will define several methods a test case for the whole class will involve all the calling each of the methods, a select set of methods and so on. Finally, the full blown object oriented testing feature is a inter class testing where more than one class is put together and tested at the same time

usually to see how they interact. We will be considering inter class and intra class testing in these lectures.

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The slide is titled "Visualizing OO interactions" in a blue header. It contains three bullet points:

- We assume that a class encapsulates state information in a collection of *state variables*. The behaviors of a class are implemented by methods that use the state variables.
- The interactions between the various classes and methods within/outside a class that occur in the presence of inheritance, polymorphism and dynamic binding are complex and difficult to *visualize*.
- We will go through some examples to illustrate the issues.

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So, now before we move on, actual testing we will see a couple of lectures later. What I am going to tell you for the rest of this lecture and in the next lecture is what are the problems what are the difficulties, what are the anomalies, what are the faults that occur due to the specific object oriented features of inheritance, presence of polymorphic methods and dynamic binding. What happens in these cases? What are the issues that can come when we do inter class and intra class testing.

So, now before we move on, the most difficult thing is when you have a large many classes each defining its set of methods it is very difficult to visualize the actual sequence calls, the actual interactions that happen amongst these classes. I will show you examples of how difficult it is. So, we want to be able to do that. So, to do that we assume that a class encapsulates all the state information that I need. This is a traditional way, there is nothing related to object oriented software in any piece of program, what is the state of a program? State of a program defines the values of all its variables along with the location counter where the program decides.

So, in object oriented programming we assume that the class as an entity, encapsulates all the state information as a collection of state variables as it is done in other programming language. So, now, the behaviors of a class; how do they come? Class is a

static entity not executable. So, the behavior of a class is implemented by a set of methods that use these state variables. The interactions between various classes and methods, methods could be inside the same class or it could be outside a class will occur in the presence of all these features, inheritance, polymorphism, dynamic binding and those are the features we want to understand and visualize how the interactions happen.

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Class hierarchy and method overriding: Example

```

1. void f(boolean b)
2. {
3.   W o;
4.   ...
5.   if(b)
6.     o = new V();
7.   else
8.     o = new W();
9.   ...
10.  o.m();
11. }

```

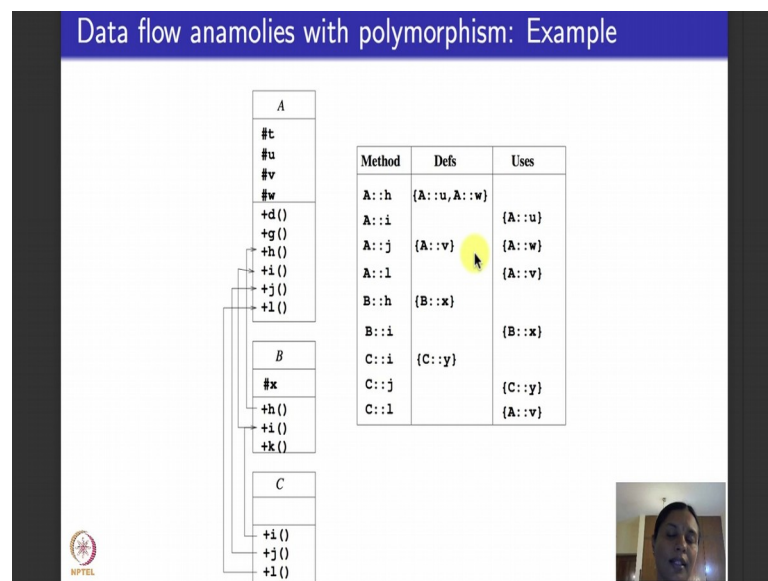
- V and X extend W, V overrides method m() and X overrides methods m() and n().
- -: attributes are private, +: attributes are non-private.
- The declared type of o is W, but at line 10, the actual type can be either V or W.
- Since V overrides m(), which version of m() is executed depends on the input flag to the method.

So, here is the first example consider this situation look at the left hand side of this figure. There are three classes W V and X and as per this picture V extends W, X also extends W. W has a private variable called small v and it has two methods m and n, V also has a method m which means this method m in V overrides the method m in W. Similarly the method m; methods m and n in X override the methods m and n in W. Minus sign indicates as I told you earlier the attributes are privates and plus sign indicates of the attributes are non private.

Now let us look at this piece of code on the right hand side. It is talking about some function f that takes a Boolean argument V and it begins by saying that the declared type of this object o is W and then there some piece of code dot dot dot read it as some piece of code and then let us say there is a new statement which says if this boolean variable b is true then you make o as what type, V. If this Boolean variable is false then you retain o to be of type W and later after some point let us say you call the method m for the object o. Now we know that the method m and V overrides the method m in W.

So, at this point in line number 10, we do not know which version of the method is called. Is Vs version of m called or its Ws version of m called that is not clear. It will purely be dependent on what the value of B is, this part here described by dot dot dot did it change B what happened to B. So, we need to know. So, usually this kind of analysis provides challenges because m overrides, the m in V overrides the m and W at this point in time we do not know which code of m got executed. So, this is the first kind of difficulty that we find in visualizing.

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Moving on here is another kind of difficulty that you find with polymorphic methods this is a slightly bigger piece of program. What does it have? It has three classes A B and C, I have put them one below the other. A has how many variables four variables t, u, v and w, and it also has six methods d, g, h, I, j and l. Just for simplicity sake we have retained them a single letters they could be any method names. And then class B has one variable x. It has two three methods h, i and k. And what do these arrows indicate? These arrows indicate that the method h in B overrides the method h in A. Similarly the method i in B overrides the method i in A.


Now there is one more class C which has three methods I, j and l. And again there are arrows from this i pointing to the i of B, going by the same interpretation read this presence of this arrow as the method i in C overrides the method i in B, the method j in C overrides the method j in A, the arrow goes all the way up to class A and the method l in

C if you go trace the arrow and go up all the way, this method, overrides the method l in A. Is this clear that is what I have written here in the next slide.

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Data flow anomalies with polymorphism: Example, contd.

- The root class *A* has four state variables and six methods, two descendents *B* and *C*. Methods of *A* are called in sequence.
- The state variables of *A* are protected, i.e., available to *B* and *C*.
- *B* declares one state variable and three methods, *C* declares three methods.
- *B::h()* overrides *A::h()*, *B::i()* overrides *A::i()*, *C::i()* overrides *B::i()*, *C::j()* overrides *A::j()* and *C::l()* overrides *A::l()*.
- Data flow anomaly: Suppose an instance of *B* is bound to an object *o* and a call to *d()* is made. *B*'s version of *h* and *i* are called, *A::u* and *A::w* are not given values, and thus the call to *A::j* can result in a data flow anomaly.



The root class *A* has four state variables six methods we saw that right, four state variables six methods. It also has two descendant classes *B* and *C* as I told you. Methods of *A* are called in sequence which means what you assume that in the code of there is some piece of code in a where method *d* calls method *g*, which in turn calls method *h*, which in turn calls method *i*, which in turn calls method *j* and *j* in turn calls method *a* that is what I have written here.

Now the state variables away as you can see in the notation are protected which means what, they are available to the descendant classes *B* and *C*. *B* declares one state variable three methods, *C* declares three methods. And we discussed this overriding which method of *B* overrides which methods *A*, which methods of *C* overrides which method of *A* and *B*.

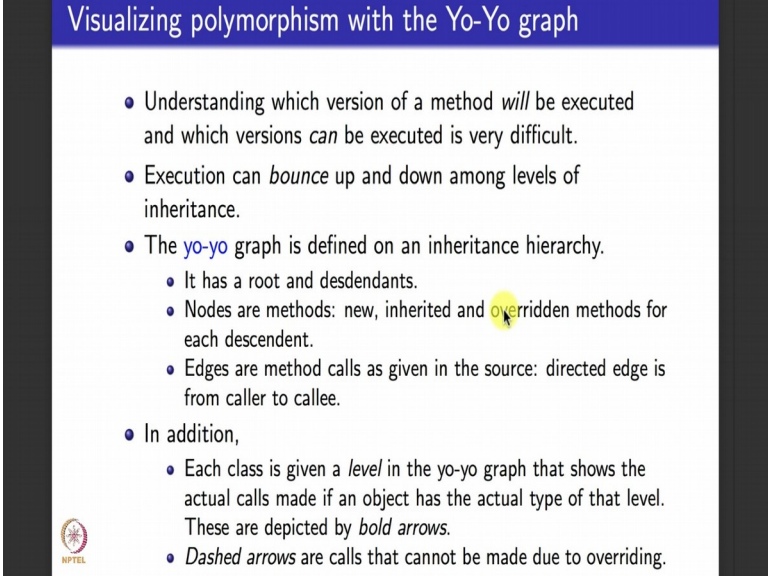
Now, consider a situation like this. What does this say? This says how to read this table this says in the method *h* as present in class *A*, two variables are defined *u* and *w*. And the variable *u* that is defined in the method *h* for *A* is used by the method *i* for *A*. Similarly the variable *v* is again defined in the method *j* present in *A* and method *j* also uses the variable *w*. The method a variable *v* defined in *j* gets used by the method *i* in *A*. Now *B* also defines a variable *x* in its method *h* *B* uses the variable *x* in its method *i*; *C*

similarly defines variable y in its method i and uses variables y and v in its method g and f. Is this clear?

Now I claim that because there are these polymorphic methods i and k and h and the j and l there is a problem with data flow. How do you understand the problem with data flow? Here is the anomaly, suppose an instance of B is bound to an object o and let us say a call to d is made, a call to d is made right. Now B's d, what will d do - d will call g g will call h, but which version of h is called, B's version of h is called right. B's version of h is called which means what - B's version of h and B's version of i is called. If B's version of h and i is called then you look at it here. B's version of h, what is the variable that it defines it defines the variable x, B's version of i defines nothing. But then what do we want we finally, want A j because a in sequence I told you right g calls g sorry d calls g which in turn calls h and i, but h and i are the B's versions that are called and I further calls, what does j need ? j needs A w because it is going to use A w, but as version of I and h were not called only B's version of h and i were called and w was not defined B's version of h defines only x, B's version of I defines nothing.


So, that is what is said here B's version of h and I are have called A u and A w are not given values because only as version of h gives them values which means what the call to a j can result in a dataflow anomaly. It does not present at all. So, how will it use W there will be a problem. So, these are the kind of faults that we want to recover, identify and test for when we do object oriented programming.

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Visualizing polymorphism with the Yo-Yo graph

- Understanding which version of a method *will* be executed and which versions *can* be executed is very difficult.
- Execution can *bounce* up and down among levels of inheritance.
- The **yo-yo** graph is defined on an inheritance hierarchy.
 - It has a root and descendants.
 - Nodes are methods: new, inherited and overridden methods for each descendent.
 - Edges are method calls as given in the source: directed edge is from caller to callee.
- In addition,
 - Each class is given a *level* in the yo-yo graph that shows the actual calls made if an object has the actual type of that level. These are depicted by **bold arrows**.
 - **Dashed arrows** are calls that cannot be made due to overriding.



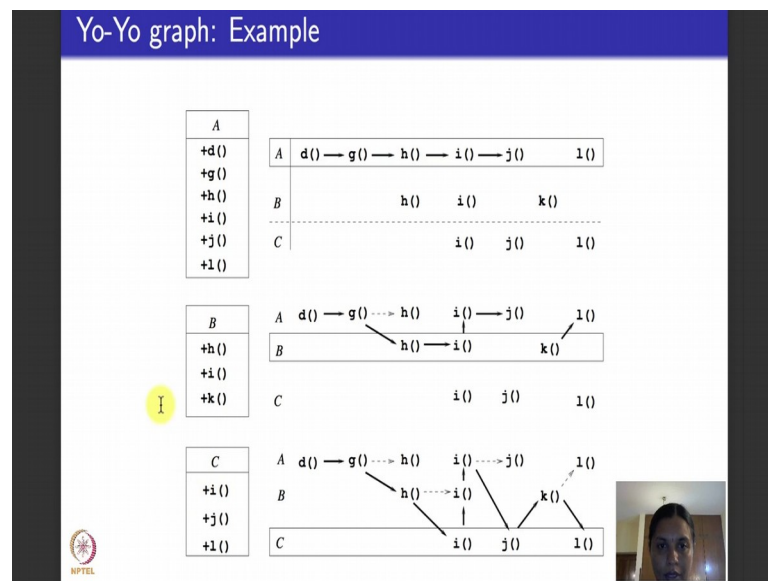
Now one last example before we move on where I introduced Yo-Yo graph formally to you. So, Yo-Yo graph deals with a problem of which is the version of the method that will be called. It is a very difficult problem to understand because the methods that can be called can bounce up the calls of the methods can bounce up and down like in a Yo-Yo that is what we will illustrate. So, what is a Yo-Yo graph? You all might be familiar with a Yo-Yo toy right this is string and then this top like thing where you can rotate the string and when you release the rotating entity from the string, it bounces up and down up and down right.

So, what we trying to say is that the method call graphs across classes can bounce up and down like a Yo-Yo. We will illustrate it for the example that we saw in this slide. So, before that what is a Yo-Yo graph. Yo-Yo graph is more like a tree it has a designated vertex called a root and then it has some descendants. What are the vertices of the graph? Vertices of the graph are not statements or anything like that, they are individual methods because we are focusing on method calls we focusing on call graph that deal with methods. So, nodes are methods, methods could be new methods, inherited ones or overridden methods for each of the descendant.

What are the edges? As I told you edges are the method calls that are given in the source code. A directed edge is present from the caller to the callee. In addition we have two other things there is a level that is given to each class in the Yo-Yo graph that shows the

actual calls made for an object if an object has a particular type of that level these are depicted by bold arrows. The Yo-Yo graph also has dashed arrows which are lighter which talk about the calls that cannot be made because the methods have been overridden. So, for the example that is given here, if you remember this method, class A six methods class B three methods class C three methods here is how the graph looks like.

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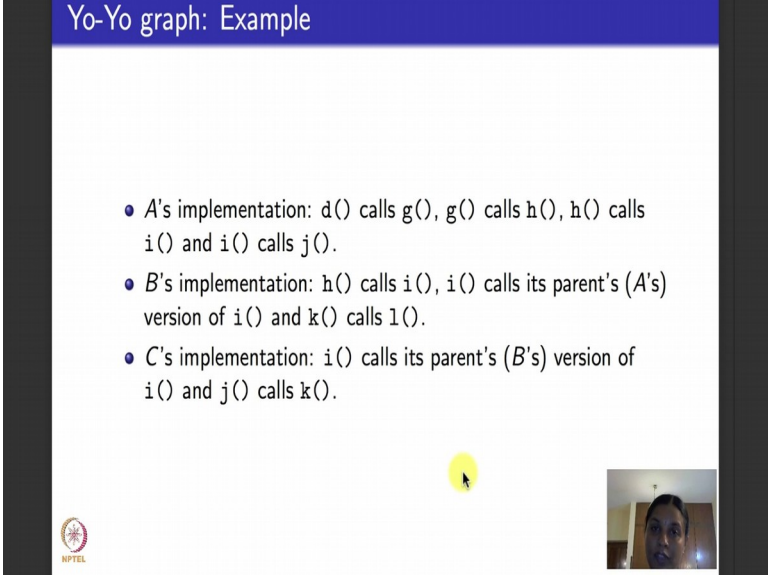
So, I have just done the left hand side here that I am tracing with the cursor, I have just copied the same thing, but I have omitted the arrow is corresponding to overriding just not to clutter the figure too much. What have I depicted here? Again it is the same information: classes A, B and C are given here this is a list of methods that are present in the class A, this is list of methods that are present for class B and here is the list of methods that are present for class C. As I told you methods and class A call each other in sequence from top to bottom, which means d calls g, g calls h, h in turn calls i, i calls j. There is no problem everything works fine because these are all methods within the class A and the calls are absolutely fine.

But let us say you get this kind of visualization, what happens here? Method d is called in A, d calls g, g calls h, but which version of h B's version of h and B's version of h in turn calls B's version of i which calls A's version of i and then calls j and independently k to l call is present. Now if you see there is a d-link because I do not know what to do.

now this makes it even worse. So, say we start similarly we say d cause g, g calls h and h does not even call B's version it called C's version of I and C again calls B's version of i which in turn calls as version of i and As version of i now goes all the way down and calls j's C which calls B's k which calls l C and so on.

So, you can see this you can think of as a Yo-Yo unrolling itself, this is a Yo-Yo bouncing back, this is a Yo-Yo bouncing back and unrolling itself. So, the pattern of calls can grow up and down like a Yo-Yo. The dashed lines as I told you here are calls that cannot be made due to overriding, but if they had been made it could have been anomaly free that is what we are trying to say here.

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The slide is titled "Yo-Yo graph: Example" and contains a bulleted list of method call sequences for three classes: A, B, and C. The sequences are as follows:

- A's implementation: d() calls g(), g() calls h(), h() calls i() and i() calls j().
- B's implementation: h() calls i(), i() calls its parent's (A's) version of i() and k() calls l().
- C's implementation: i() calls its parent's (B's) version of i() and j() calls k().

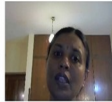

The slide also features a yellow circular cursor icon and a small video inset of a person in the bottom right corner.

So, what I explained to you is what is written here. In A's implementation there is the sequence of method calls, in B's implementation there is the sequence of method calls h calls i and i calls its parent version of i as I told you here right I calls its parent version, parent is A so it calls its parent version of i and k calls l. In C's implementation I calls this I of C calls its parent version of i which is B's i which in turn calls A's i and then the call to j is made. So, the calls of methods go flat, bounce up, bounce down like a Yo-Yo hence the term Yo-Yo graph.

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Yo-Yo graph: Example



- Top level: A call is made to method `d()` through an object of actual type `A`.
 - This sequence of calls is simple and straightforward.
- Second level: Object is of actual type `B`. When `g()` calls `h()`, the version of `h()` defined in `B` is executed. The control then continues to `i()` in `B`, `i()` in `A` and then to `j()` in `A`.
- Third level: Object is of actual type `C`. Control proceeds from `g()` in `A`, to `h()` in `B` to `i()` in `C`, then, to `i()` in `A` and `B` etc— exhibiting a yo-yo effect.



Now, if the top level call is made then there is absolutely no problem. For second and third level you could have data flow anomalies as we saw in this example. So, this is another kind of visualization that we will like to work on.

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Next lecture: Categories of inheritance faults and/or anomalies.



I will stop here for this lecture. In the next lecture I will discuss with you about specific faults and anomalies that can occur due to inheritance and polymorphism.

Thank you.