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# An Object-Oriented logic for software analysis and design

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JAIST

2005.9.21



# Background

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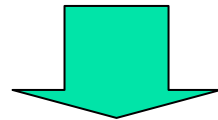
- The Object-Oriented method has become the mainstream of software development.
- In the upstream phase of the development, analysis models are constructed with a language such as UML.
- To ensure that the system satisfies its requirements, formal verification method must be applied to the analysis models.



# Verification target

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- Invariant properties about object attributes.  
e.g.
  - AC: The thermometer value always less than 30.
  - Bank: Balance values never become negative.



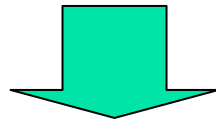
**Apply theorem proving**



# The HOL system

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- The use of HOL theorem prover
  - Interactive prover of higher-order logic.
  - A lot of mathematical libraries.
  - No libraries which implement OO concepts.



**Implement object theory in HOL**



# Existing object theories in higher-order logic

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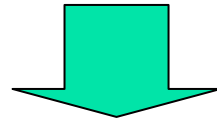
- Semantics of Java program verification
  - LOOP, Bali, Krakatoa, ...
    - Types of object attributes are limited to primitive ones appearing in Java (integer, boolean, ...).
  - Compared to program verification, analysis model verification requires high availability of types.
    - High abstract types (set, stack, tree ...)
    - Domain-specific types (date, time, currency, ...)



# Objective

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- Implement an object theory where object can have arbitrary types of attributes.



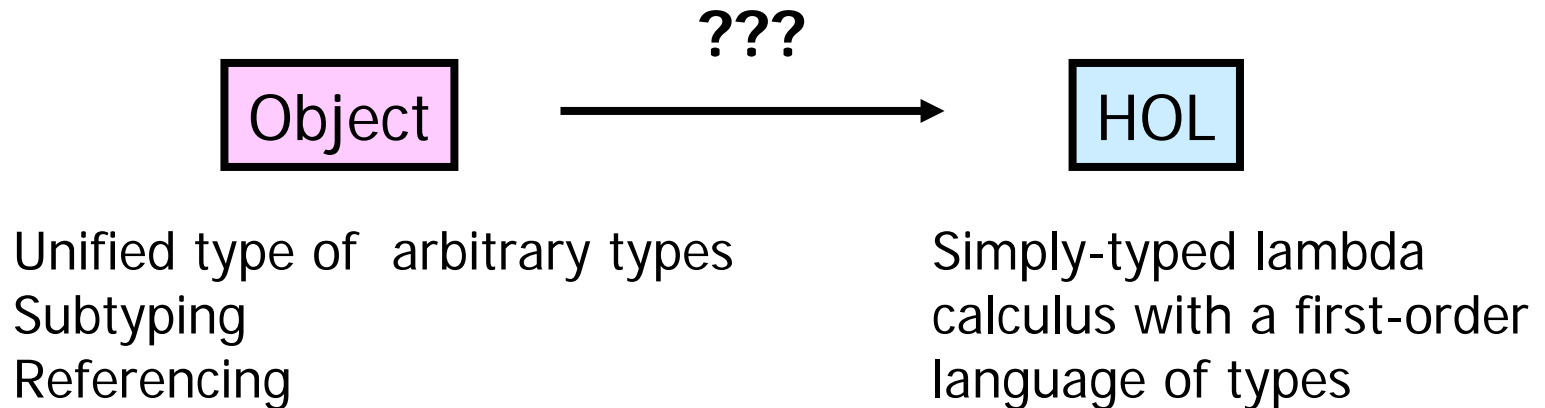
Verification with a wide variety of types becomes possible making use of plentiful mathematical libraries and powerful datatype definition facilities of HOL.



# Embedding problem

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- The type system of HOL is too simple to express object concepts as a general type.



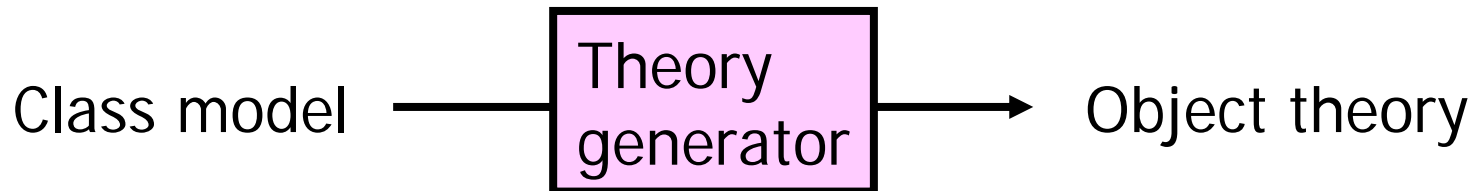




# Approach

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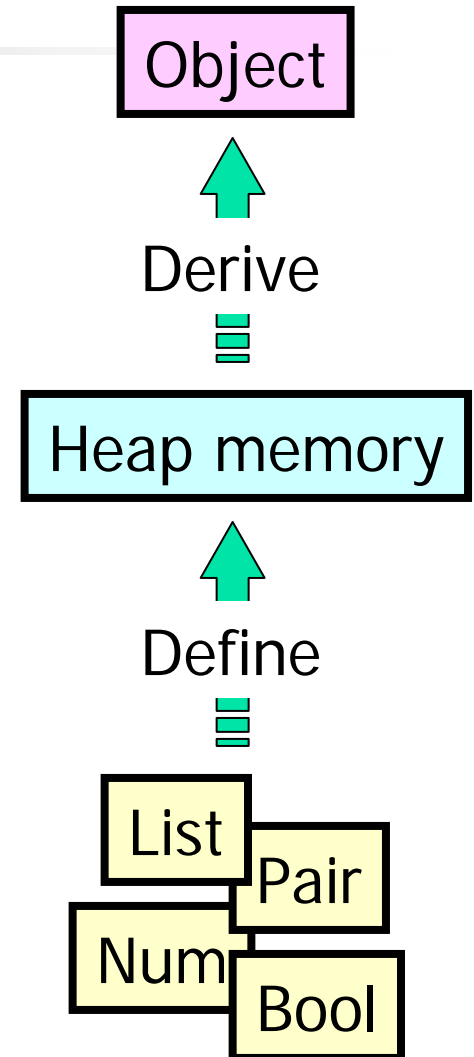
- **Application-specific theory**
  - Automatically construct object theories depending on the type information of individual applications.



➡ In effect, arbitrary types can be incorporated into object attributes.

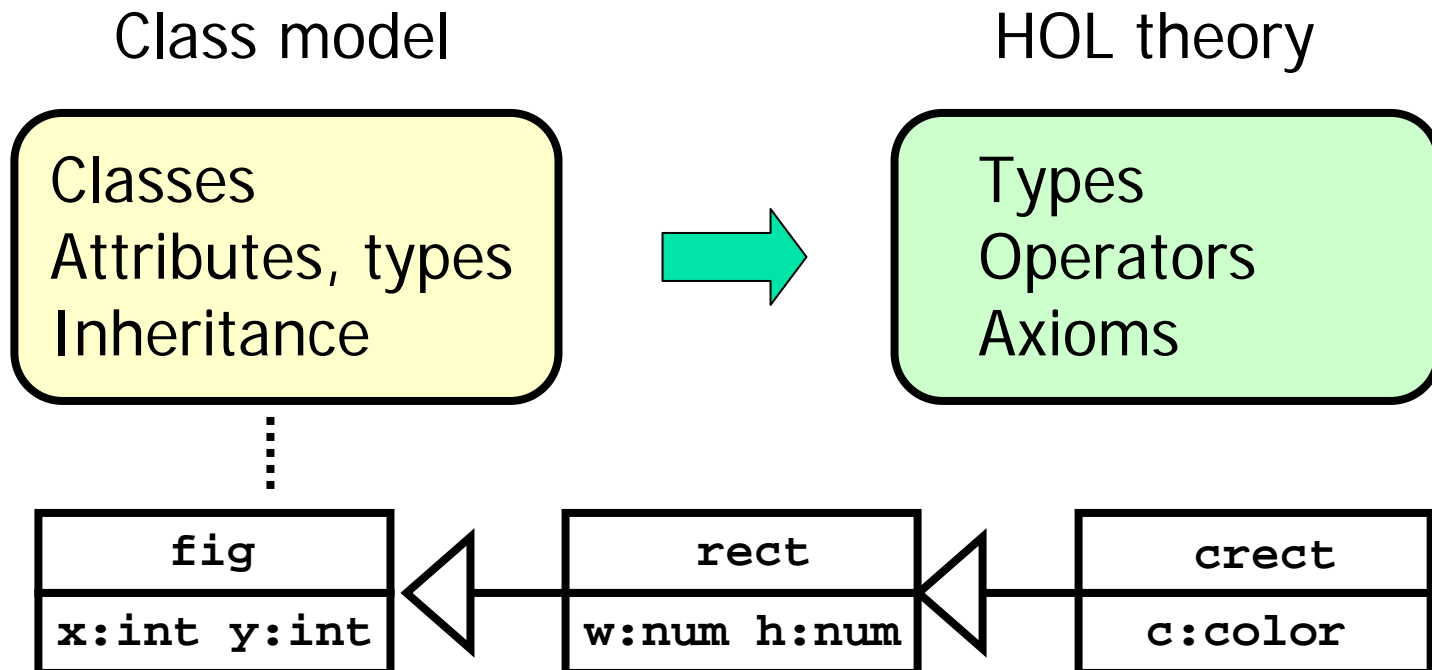
# Soundness

- Construct the theory by **definitional extension**
  - The standard technique to construct sound theories in HOL
  - Derive new theories from existing sound theories only by introduction of definitions and derivation by sound inference rules.



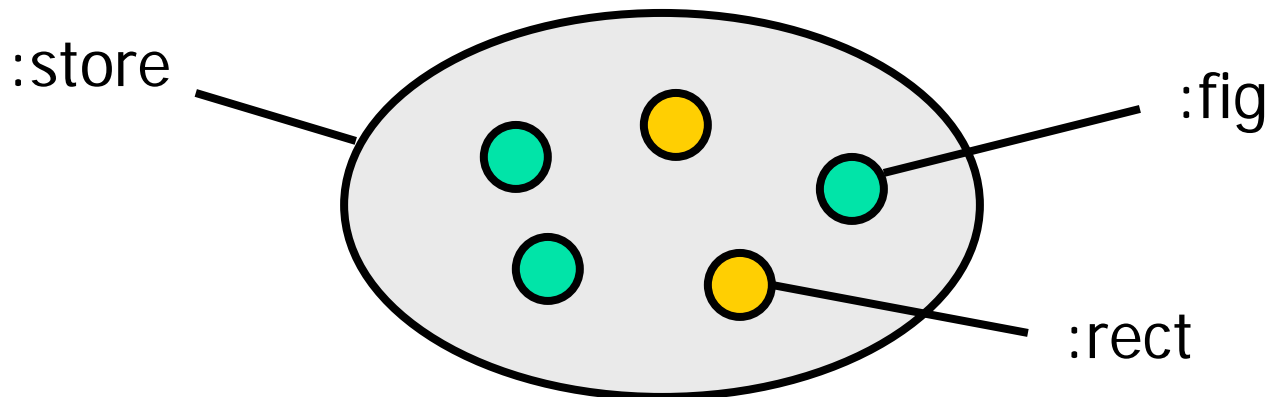
# Overview of the theory

- The theory is defined by mapping the class model elements to theory elements



# Types

- Store
  - The environment of a system which holds a state of all alive objects.
- Object references
  - Object references are represented by types whose names are their class names.





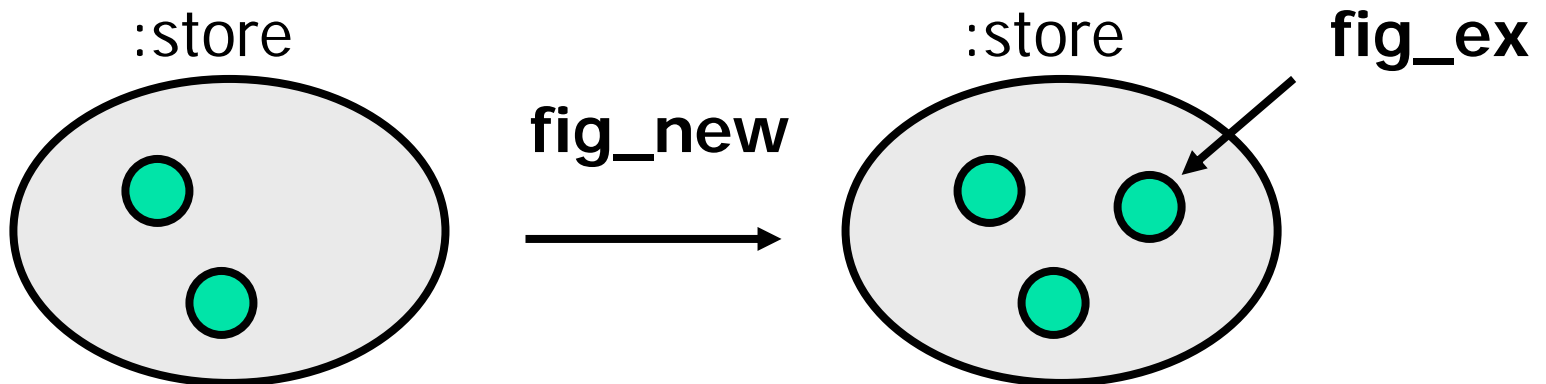
# Operators & axioms

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- 6 kinds of primitive operators to handle objects are defined on the store.
  - Object creation
  - Alive test
  - Attribute read
  - Attribute write
  - Casting
  - Instance-of
- 36 axioms are introduced on the operators.

# Object creators & alive testers

- Object creators creates a new object in a store.
- Alive testers tests if an object exists in a store.

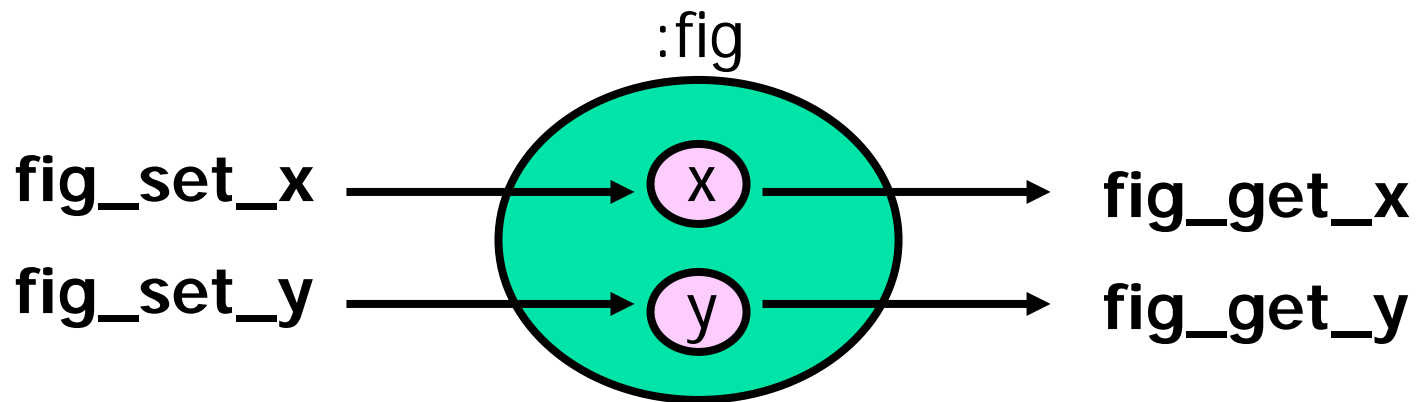


```
f s. let (f,s') = fig_new s in fig_ex f s'
```

**"The newly created object exists in the new store."**

# Attribute accessors

- Attribute accessors read and write the object attributes.

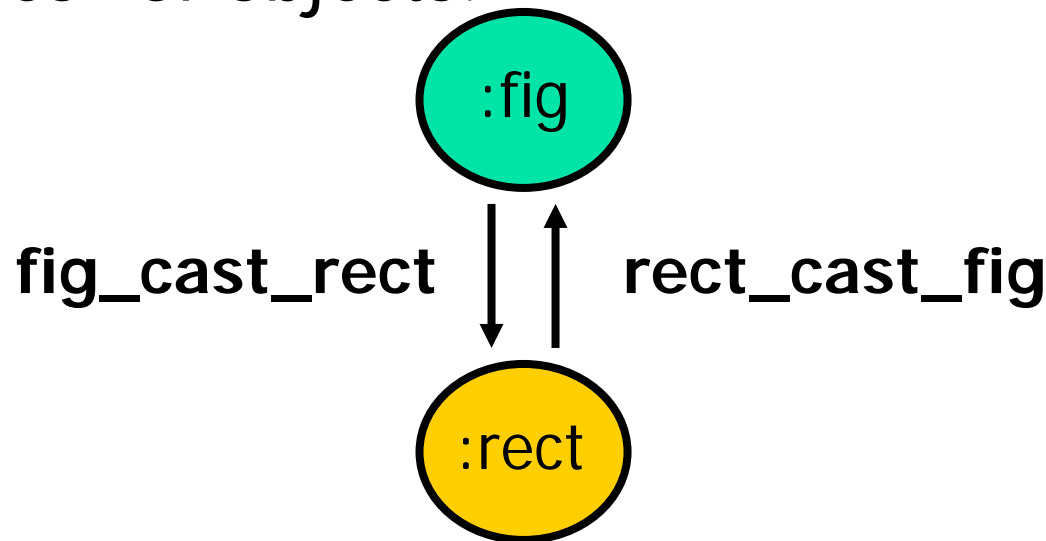


```
f x s. fig_ex f s  
  (fig_get_x f (fig_set_x f A s) = A)
```

"The attribute x obtained just after updating it to A is equal to A."

# Casting functions

- Casting functions change the “apparent types” of objects.



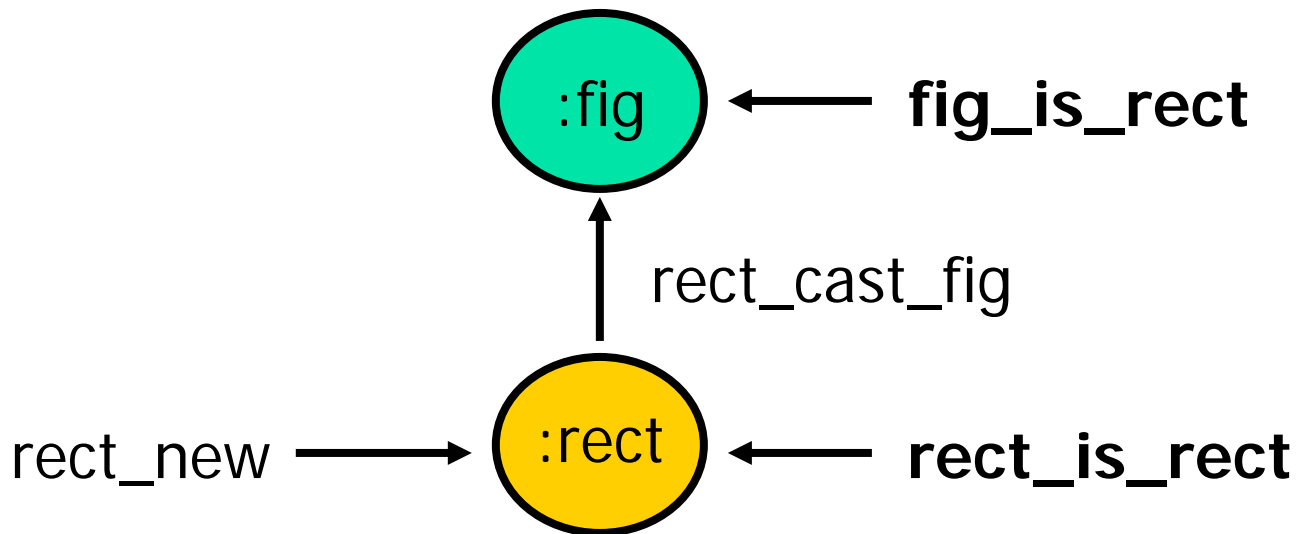
```
r s. rect_ex r s
  (fig_cast_rect (rect_cast_fig r s) s = r)
```

“Upcasting and downcasting results in the original object.”



# Instance-of predicates

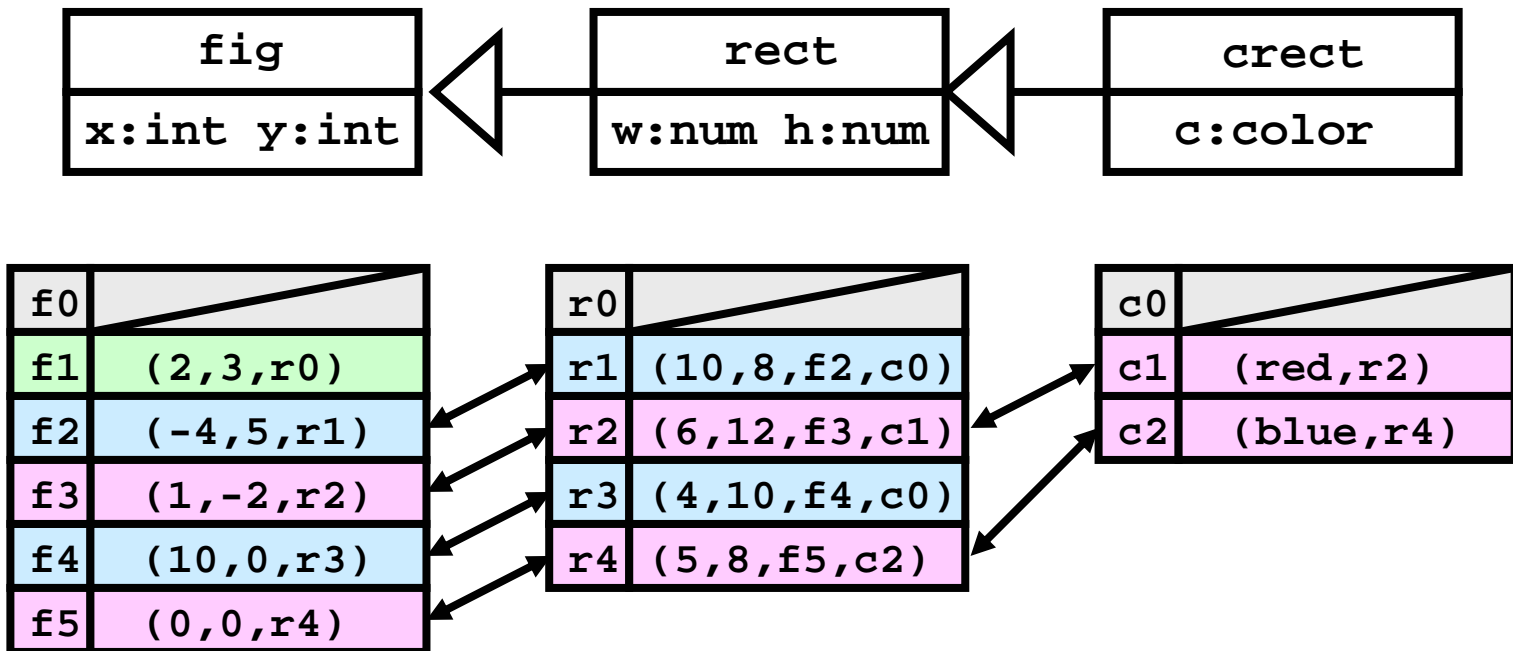
- Instance-of predicates remember the “actual types” of objects.



```
r s. rect_is_rect r s
    fig_is_rect (rect_cast_fig r s) s
```

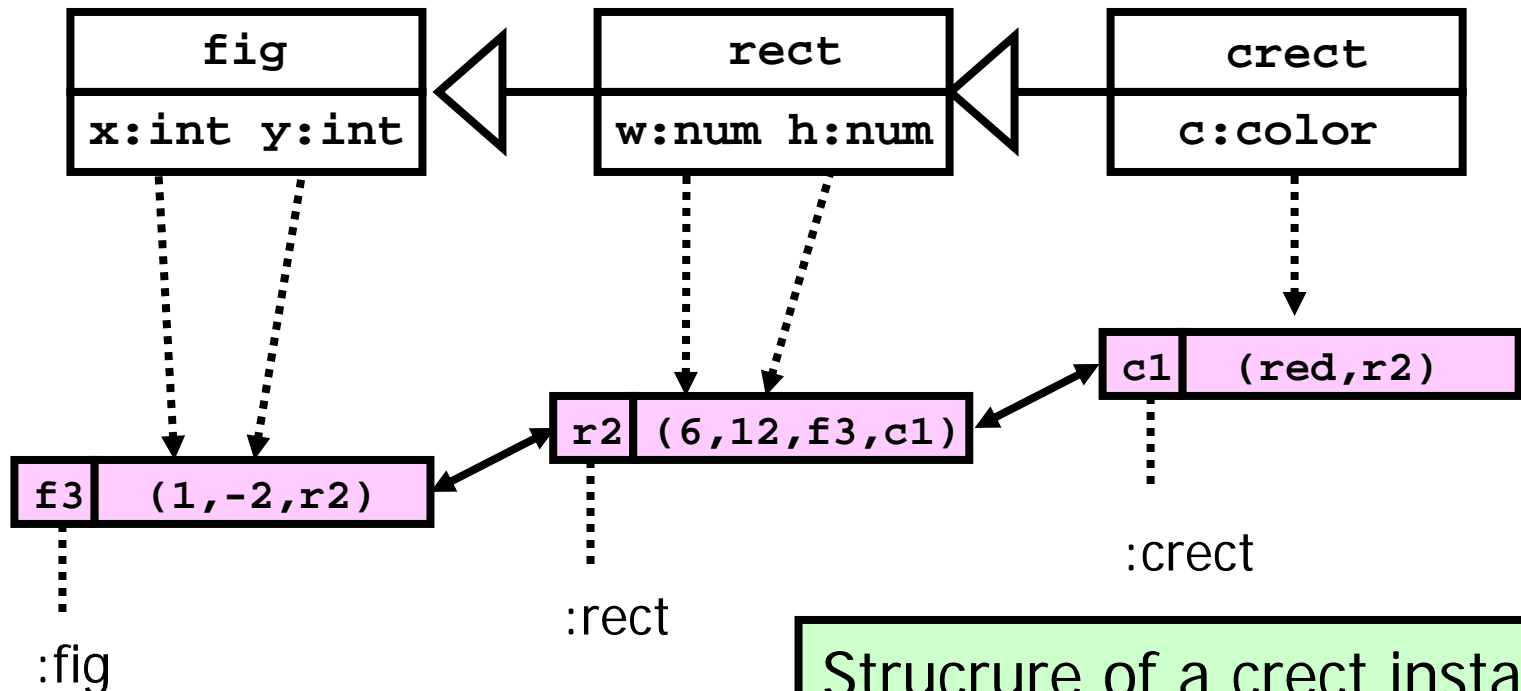
# Heap memory model

- The theory is derived from the operational semantics of a heap memory model.



# Object structure

- Subtyping mechanism is implemented by composing a single instance by multiple cells.



Structure of a crect instance



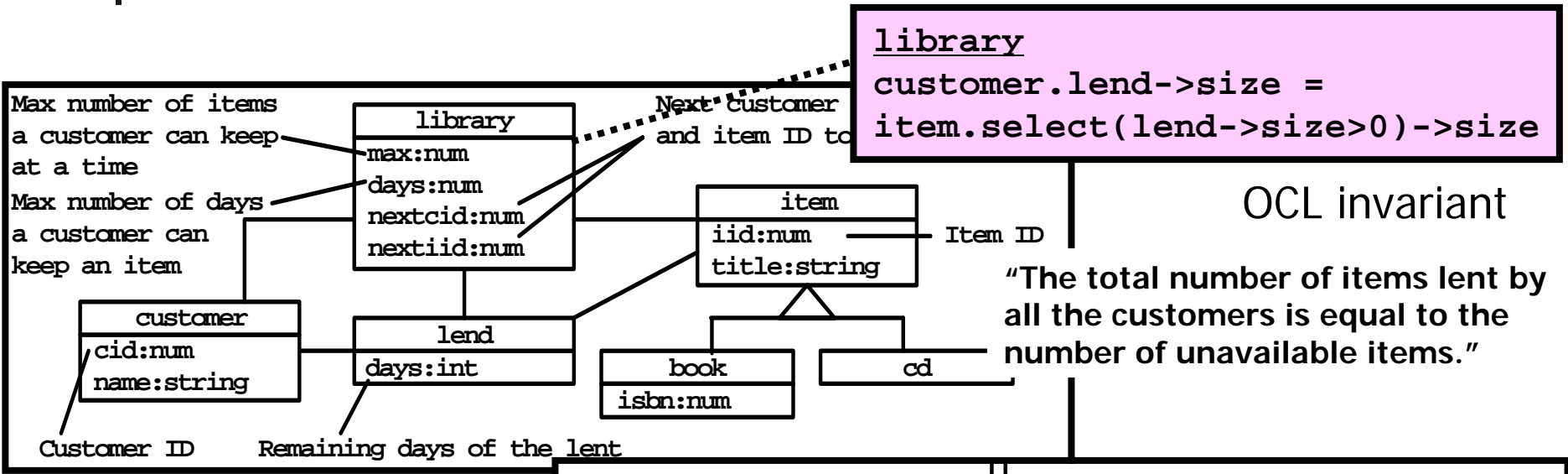
# Prototype execution

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- The theory is executable in moscow-ML
  - Define the operational semantics of the heap memory model as actual operations in ML.

```
- val (f,s1) = fig_new store_emp;  
> val f = <fig> : fig  
> val s1 = <store> : store  
- val s2 = fig_set_x f 10 s1;  
> val s2 = <store> : store  
- val x = fig_get_x f s2;  
> val x = 10 : int
```

# Example: a simple library system



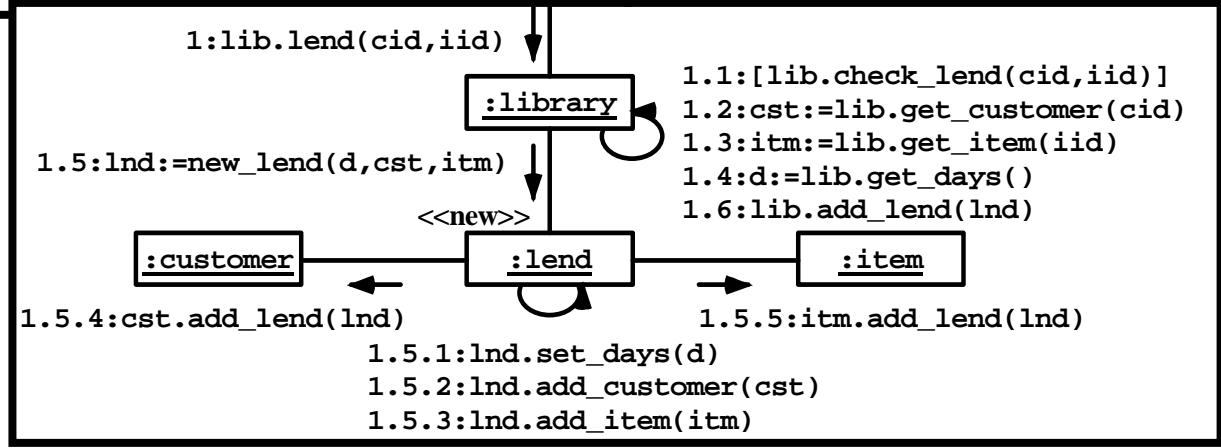
library

```
customer.lend->size =
item.select(lend->size>0)->size
```

OCIL invariant

"The total number of items lent by all the customers is equal to the number of unavailable items."

Class diagram



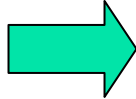
Collaboration diagram of lending service

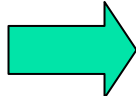


# Invariant verification

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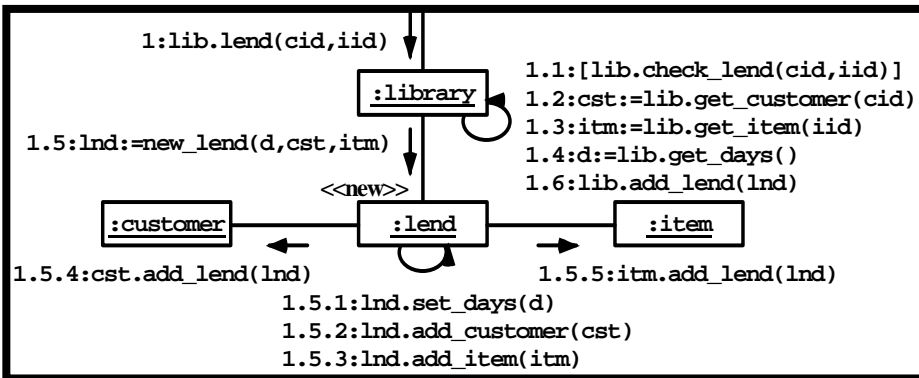
- Verify that the collaboration maintains the invariant.

**Collaboration**          **F : store -> store**

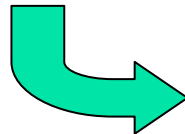
**Invariant**                  **P : store -> bool**

- s. P (s)     P (F (s))
--------------------------

# Collaboration definition in HOL



Collaboration diagram  
of the lending service



HOL representation of  
the collaboration

```

library_lend lib cid iid s =
  if library_check_lend lib cid iid s then
    let cst = library_get_custmer lib cid s in
    let itm = library_get_item lib iid s in
    let d = library_get_days lib s in
    let (lnd,s1) = new_lend cst itm d s in
    let s2 = library_add_lend lib lnd s1 in
      ("ok", s2)
  else ("fail", s)
  
```

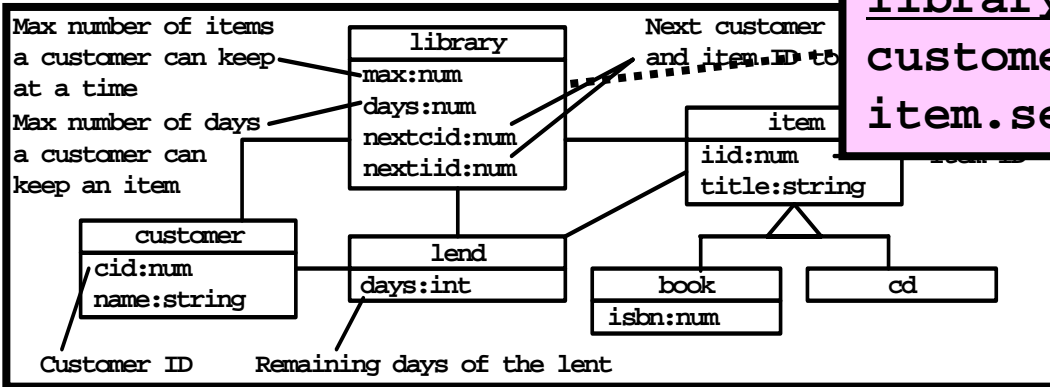
```

new_lend cst itm d s =
  let (lnd,s1) = lend_new s in
  let s2 = lend_set_days lnd d s1 in
  let s3 = lend_add_customer lnd cst s2 in
  let s4 = lend_add_item lnd itm s3 in
  let s5 = customer_add_lend cst lnd s4 in
  let s6 = item_add_lend lnd s5 in
    (lnd, s6)
  
```

```

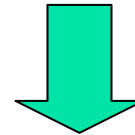
Library_get_customer lib cid s =
  let l = library_get_customerlist lib s in
  FST (FILTER
    (λx. customer_get_cid x s = cid) l)
customer_add_lend cst lnd s =
  let l = customer_get_lendlist cst s in
  customer_set_lendlist (lnd::l) s
  
```

# Invariant definition in HOL



library  
`customer.lend->size =  
item.select(lend->size>0)->size`

OCaml invariant



```

Inv lib s = library_ex lib s ==>
  (library_get_customer_lendsum lib s = library_get_item_lendsum lib s)

library_get_customer_lendsum lib s =
  let l = library_get_customer_list lib s in
  SUM (MAP (λx. customer_get_lendnum x s) l)

library_get_item_lendsum lib s =
  let l = library_get_itemlist lib s in
  LENGTH (FILTER (λx. ~(item_is_available x s)) l)

customer_get_lendnum cst s = LENGTH (customer_get_lendlist cst s)
item_is_available itm s = (LENGTH (item_get_lendlist itm s) = 0)
  
```

HOL representation  
of the invariant





# Proof

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- The collaboration of the lending service maintains the invariant.

```
|-   lib cid iid s.  
    Inv lib s  
    Inv lib (library_lend lib cid iid s)
```



# Related work

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- Object embedding using extensible records
  - W. Naraschewski et al. 1998
  - No referencing concept.
- Axiomatic semantics of UML models
  - T. Aoki et al. 2001
  - Directly introducing axioms in HOL.
- UML/OCL verification in B
  - R. Marcano et al. 2002
  - Methods are defined only by attaching pre- and post-conditions.



# Conclusion

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- Defined an object theory for analysis model verification in HOL
  - Application-specific
  - Sound
  - Executable
- Verification of a library system
  - Verify a collaboration maintains an invariant.



# Future work

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- Make the proof efficient
  - Define a collaboration as a sequential OO program and implement verification condition generator.
- COE-related work (security)
  - Verify security requirements of a system using the object theory.
    - FW: bad packets never goes into the internal network.