22c181:
Formal Methods in Software Engineering

The University of Iowa

Spring 2008

Introduction to OCL

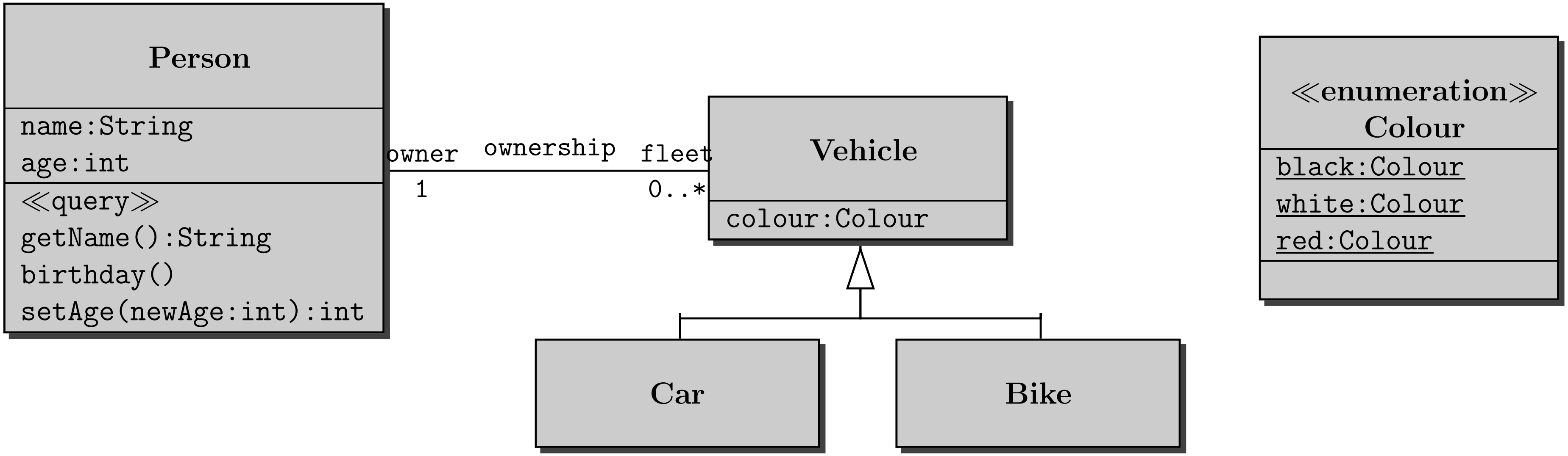
Contents

Object Constraint Language (OCL)

- Part of the UML standard
- Formal Specification Language

  Standardized formal semantics from OCL 2.0 onwards
- In this course: OCL 1.5
  - Semantics by mapping to typed FOL
  - Not all features realized, some extra features
- OCL syntax less mathematical,
  more programming language-oriented than Z, RSL, FOL, etc.
- Why OCL? UML is not expressive enough!

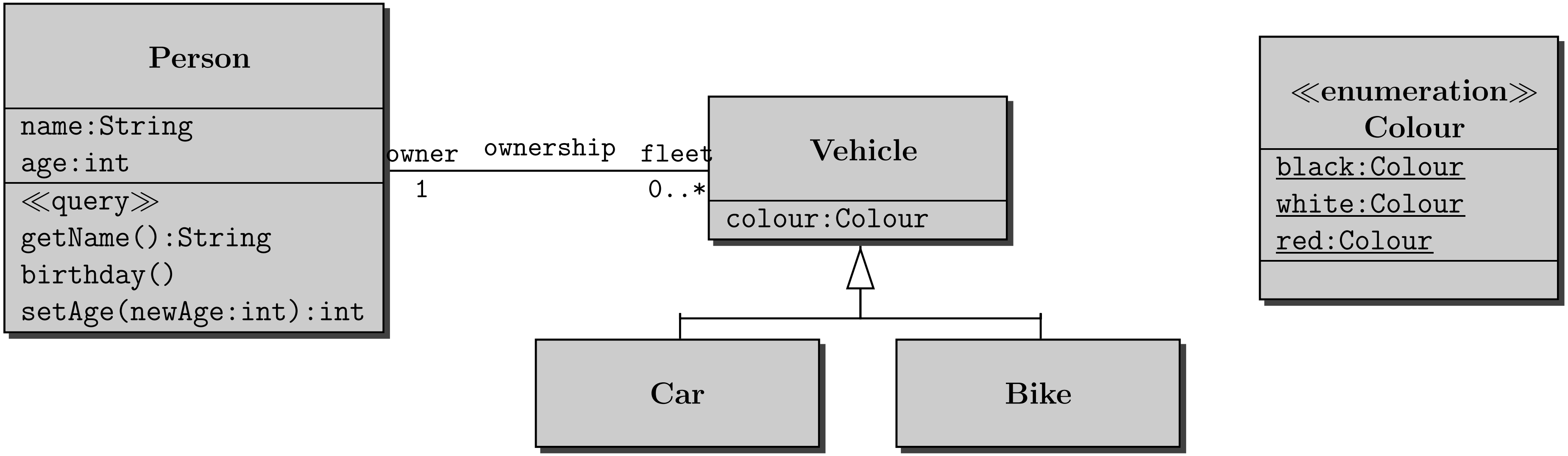
UML is not enough . . .



- **How old must a car owner be?**
- **How to express that a person can own at most own one black car?**
- **How to specify that value of age is `i` after calling `setAge(i)`?**

UML unsuitable to express semantics of design

Some OCL examples I



“A vehicle owner must be at least 18 years old”:

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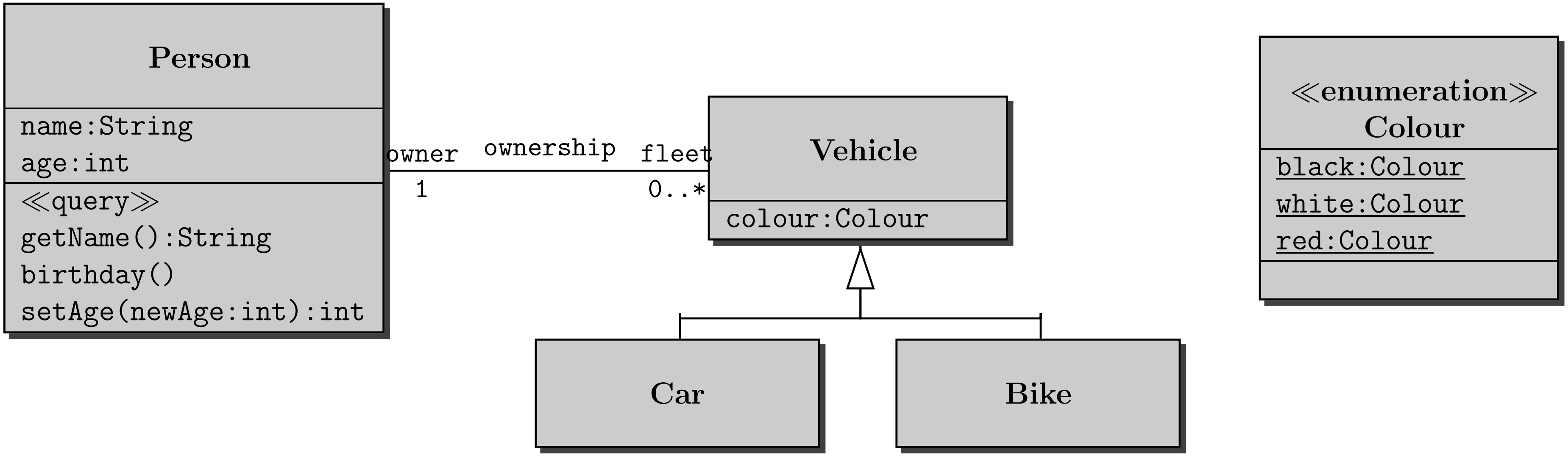

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context **Vehicle**

inv **:** **self. owner. age** $>=$ **18**

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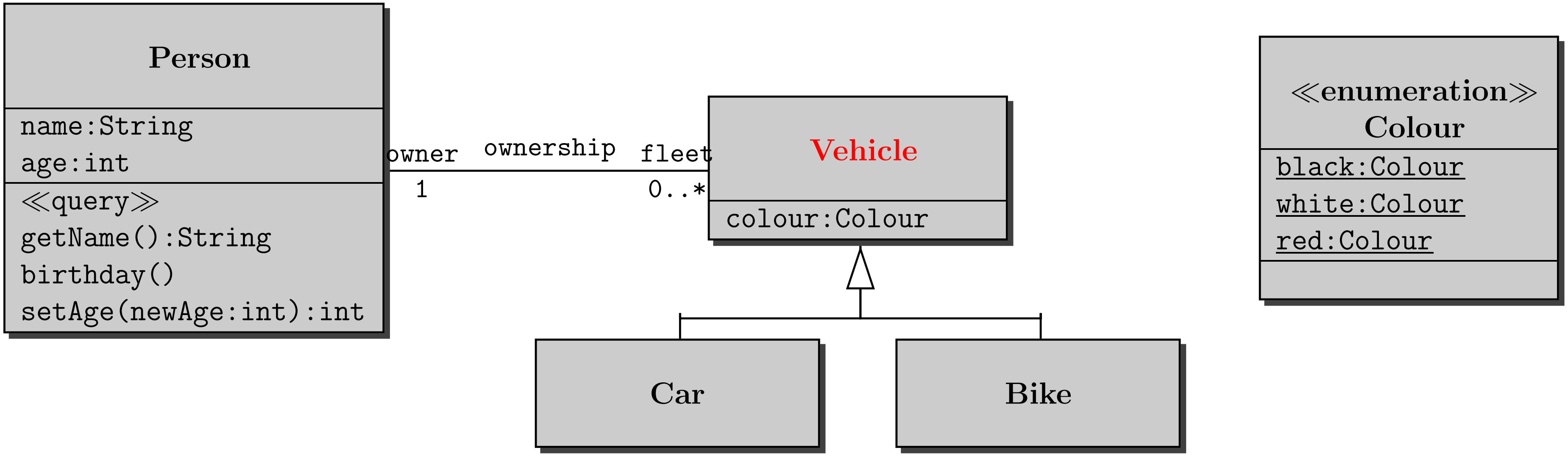
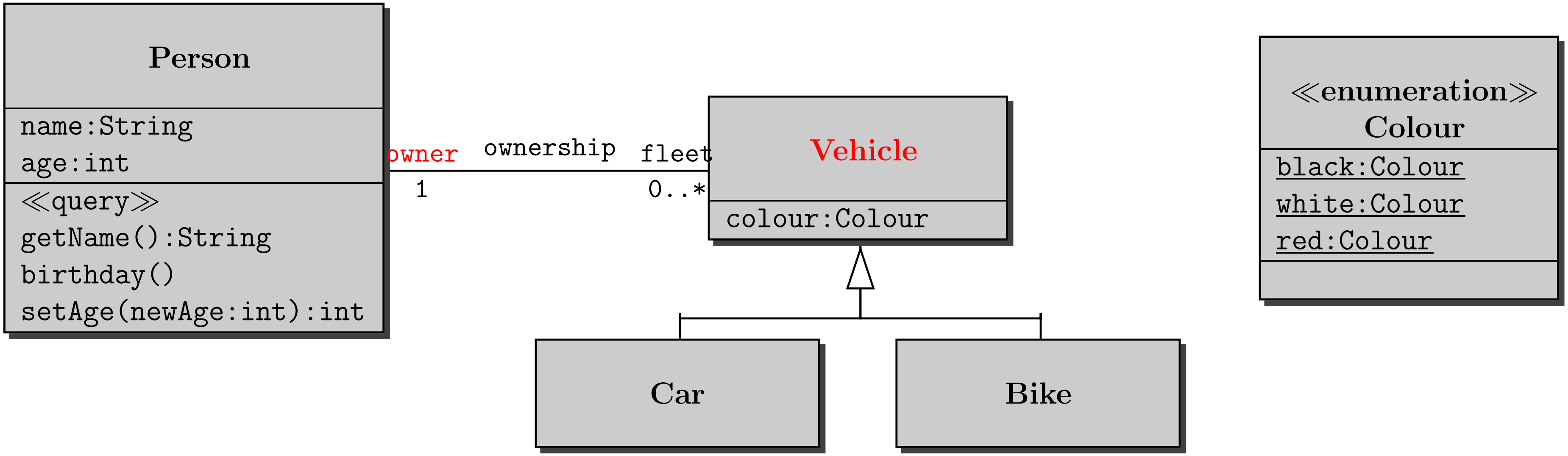


"A vehicle owner must be at least 18 years old":

context **Vehicle** **- - context declaration for all instances of this class**

inv : self. owner. age $>=$ 18 **- - 'self' is like JAVA's 'this'**

Some OCL examples I

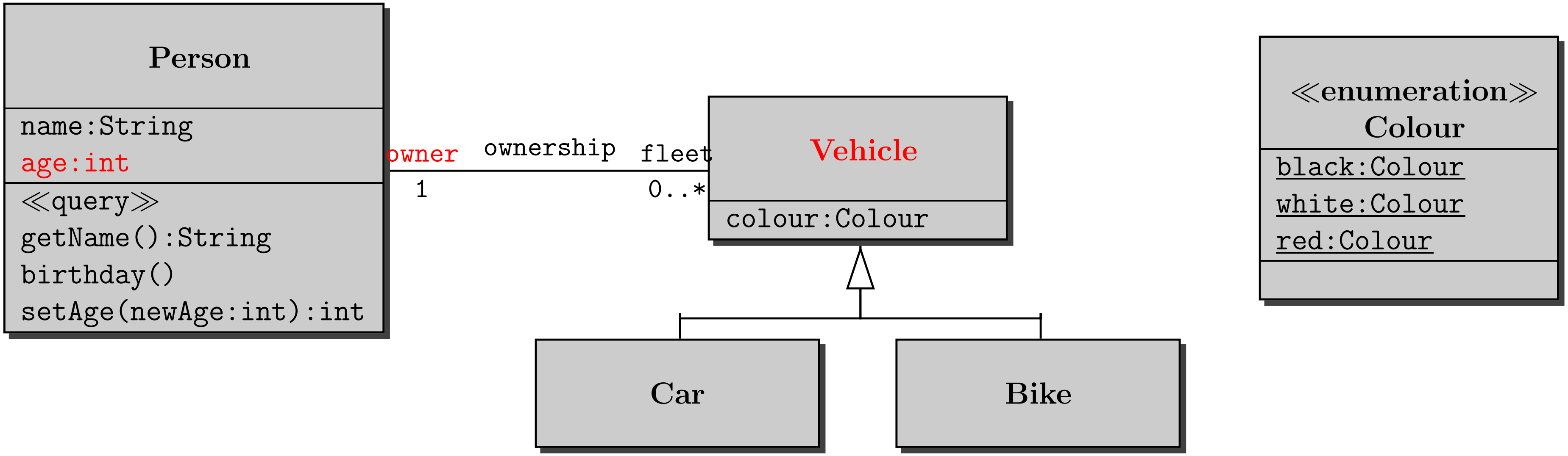


"A vehicle owner must be at least 18 years old":

context **Vehicle**

inv : **self. owner. age $>=$ 18** **- - navigate to instance of supplier**

Some OCL examples I



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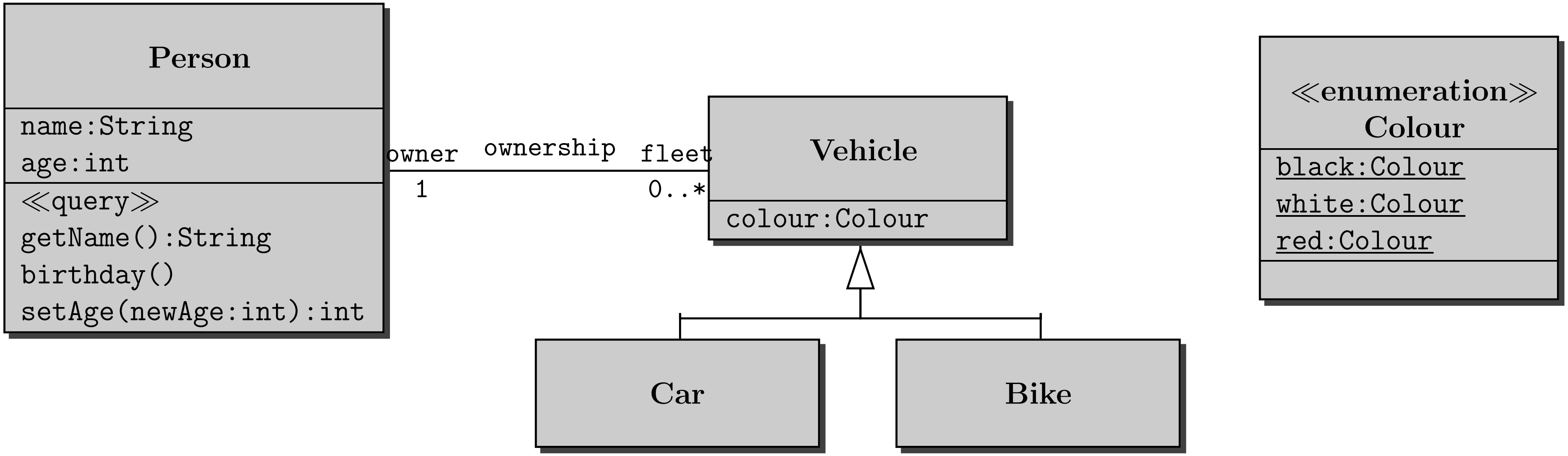

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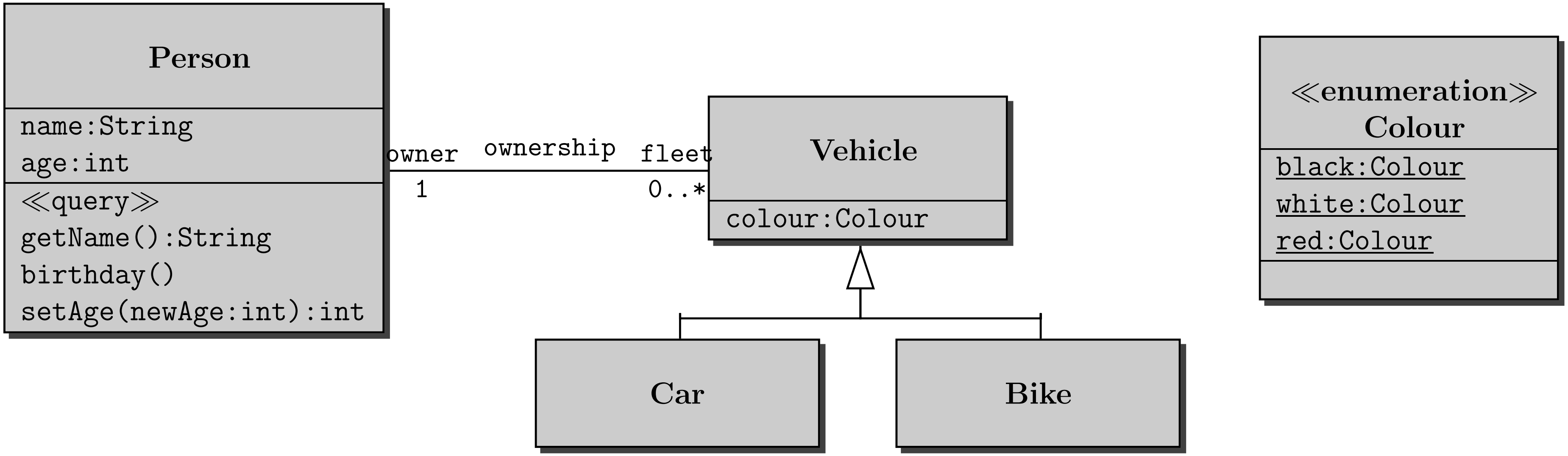


"A vehicle owner must be at least 18 years old":

context **Vehicle**

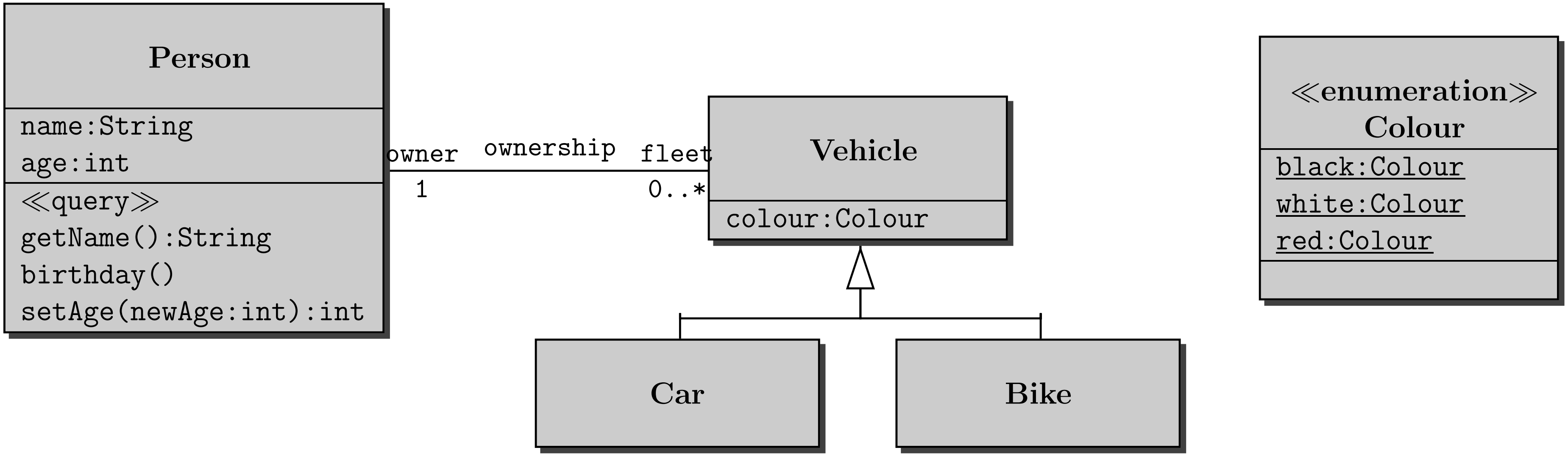
inv : **self. owner. age** $>=$ **18**

What does that mean, instead? Relation between the constraints?

context **Person**

inv : **self.age** $>=$ **18**

Some OCL examples I



“A vehicle owner must be at least 18 years old”:

context **Vehicle**

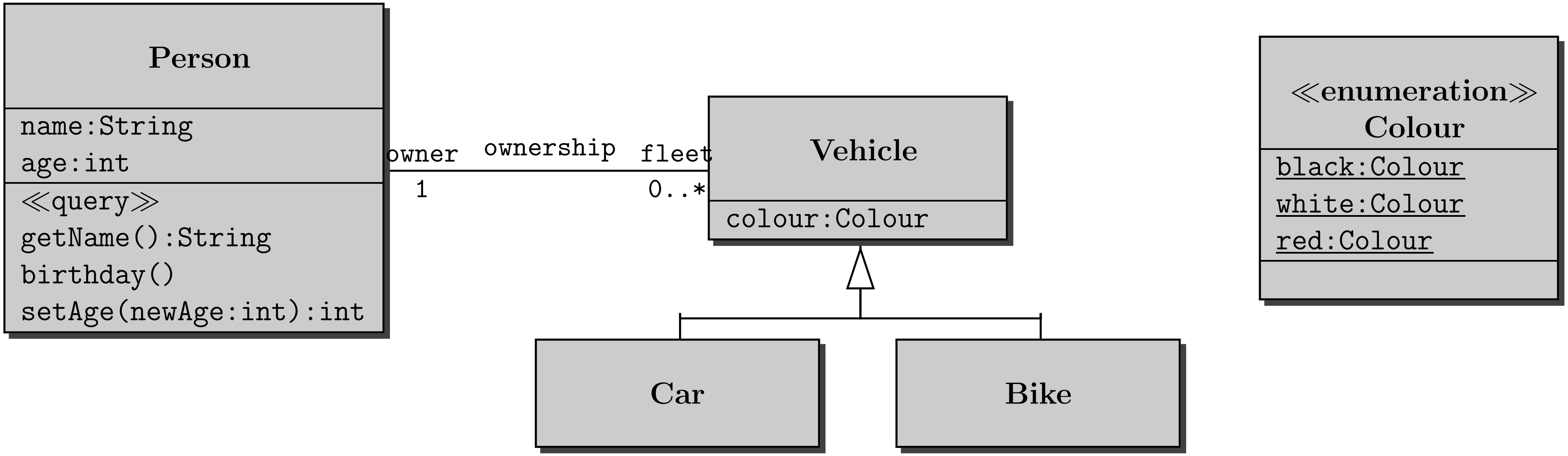
inv : **self. owner. age** $>=$ **18**

“A car owner must be at least 18 years old”:

context **Car**

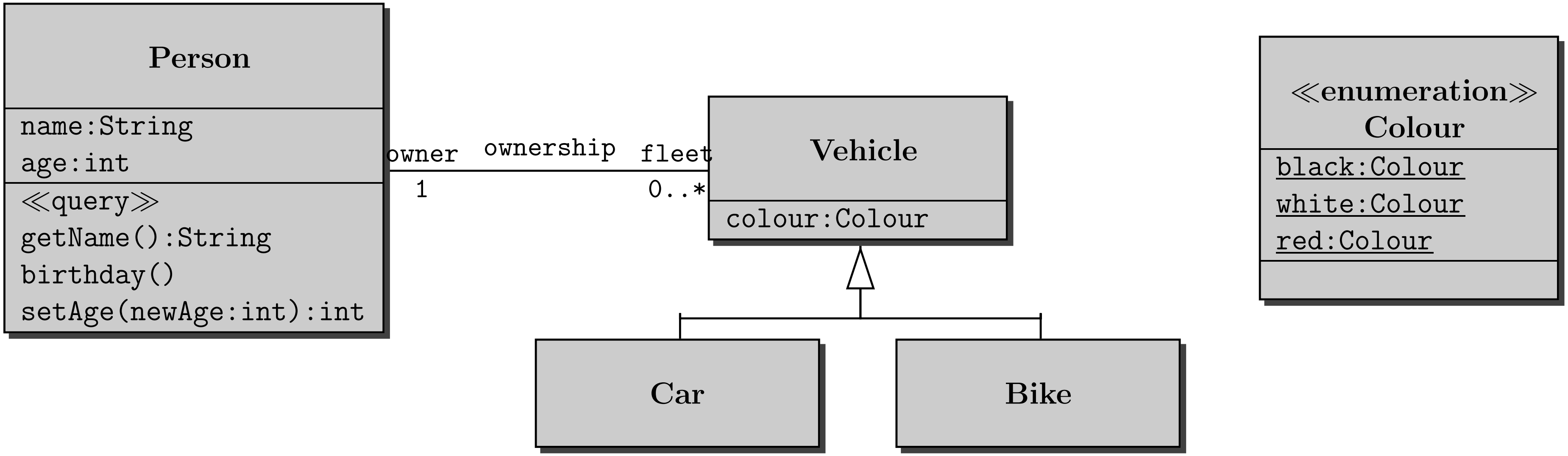
inv : **self.owner.age** $>=$ **18**

Some OCL examples II



“No person owns more than 3 vehicles”:

Some OCL examples II



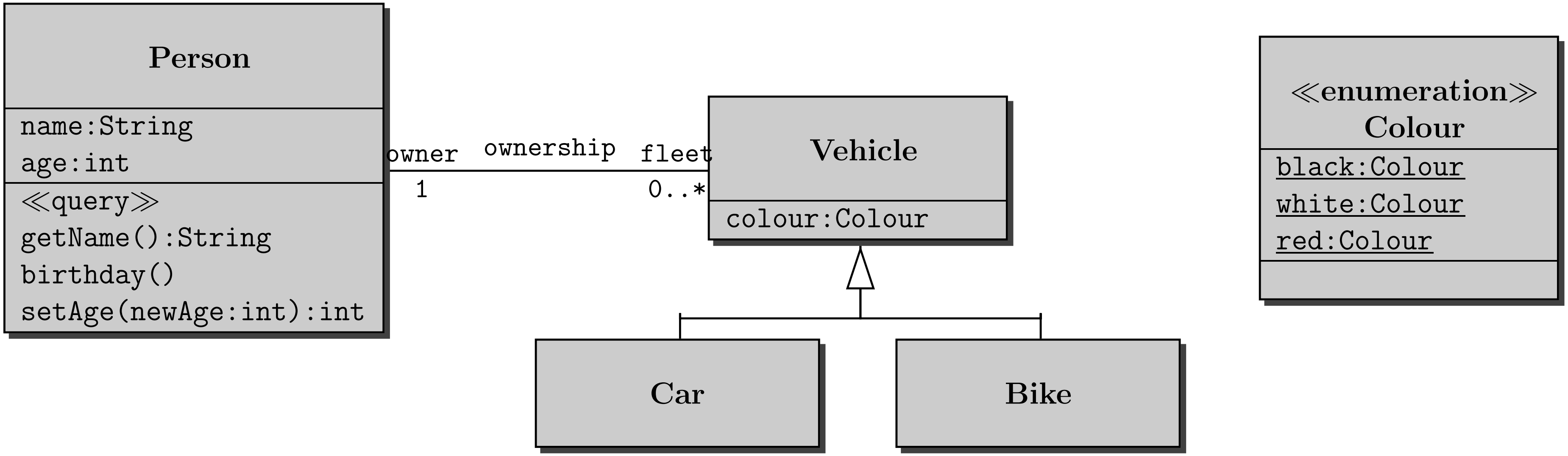
“No person owns more than 3 vehicles”:

context **Person**

inv : **self.fleet->size() <= 3**

or change multiplicity

Some OCL examples II



“All vehicles of a person are black”:

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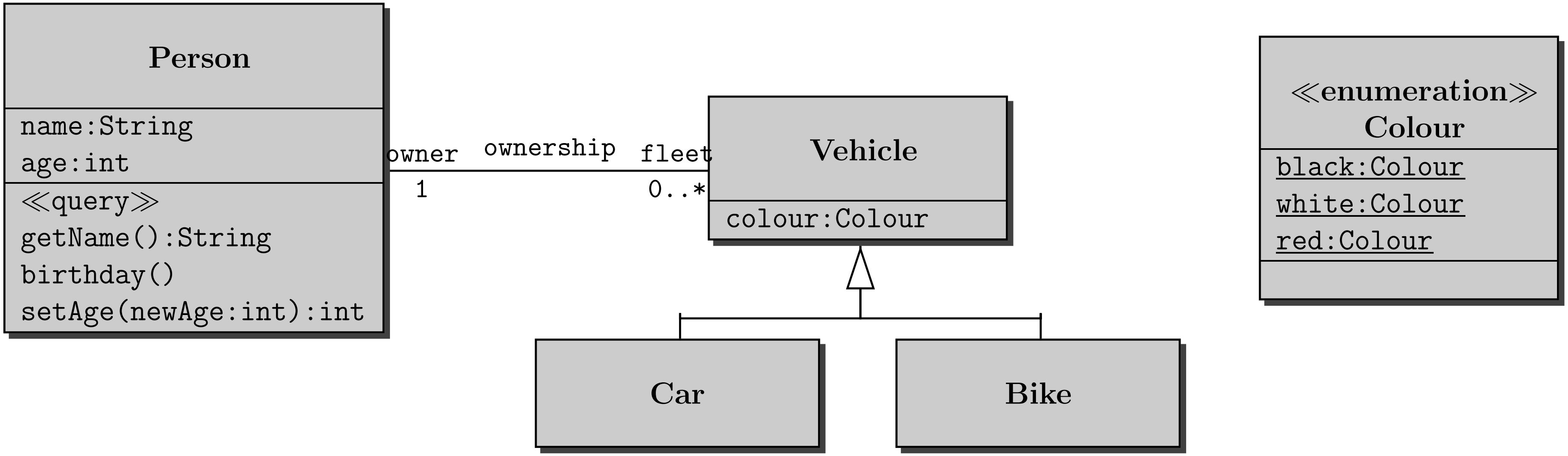

“All vehicles of a person are black”:

context **Person**

inv **: self.fleet–>forAll(v | v.colour = Colour.black)**

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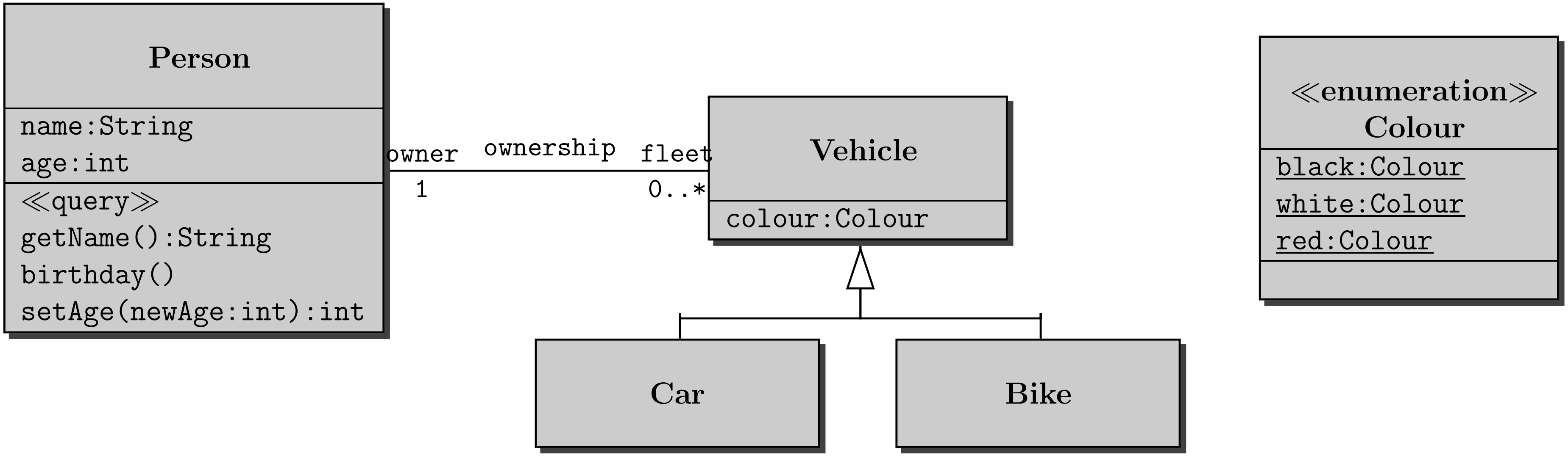

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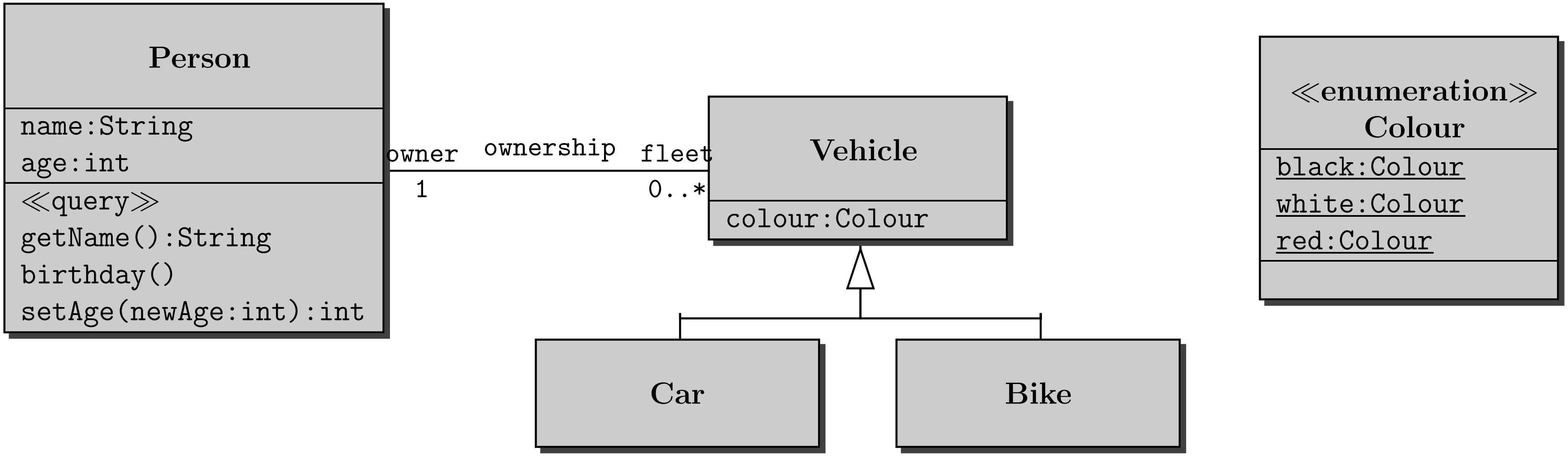

“All vehicles of a person are black”:

context **Person**

inv : **self.fleet–>forAll(v | v.colour = Colour.black)**

“No person owns more than 3 black vehicles”:

context **Person**

inv : **self.fleet–>select(v | v.colour = Colour.black)–>size() <= 3**

The Classifier Context

context [instanceName :] classPath – – class from UML model

  inv [invariantName] : oclExpression

context aCar:Car

  inv minimumAge: aCar.owner.age $>=$ 18

- Class classPath is context of invariant constraint
- Invariant must hold for all instances of classPath at all times

  Instances can be named invariantName (not in Together)
- May declare invariantName for the constraint (not in Together)
- Type of oclExpression must be Boolean

The Classifier Context

context [instanceName :] classPath – – class from UML model

inv [invariantName] : oclExpression

context [instanceName :] classPath

inv [invariantName$_1$] : oclExpression$_1$

...

...

inv [invariantName$_n$] : oclExpression$_n$

More than one invariant can be declared in same context

When Do Invariants Hold?

Consider $\mathrm{insert}()$ **operation for** List **type with attribute** $\mathrm{length} : \mathrm{int}$

- **Assume the invariant of** List **states that**

  the number of nodes in a list is equal to the value of length

- **During execution of** $\mathrm{insert}()$ **usually the invariant is violated**

Therefore, semantics of invariants in KeY and OCL:

Invariants hold at all times before and after execution of operations

How to relax this rigid requirement is topic of active research

The Operator Context: Contract

Specifying the semantics of operations: their contract

context [instanceName :]

classPath ::opName(p_1: type$_1$; . . . ;p_k: type$_k$)[:resultType]

{pre [preName] : oclExpression }

{post [postName] : oclExpression }

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Example

"Calling getName() returns the current value of the attribute name"

context Person::getName():String

post : result = name

Special variable result contains return value, has type resultType

Together 6.2 Syntax for OCL Context Declarations

Classifiers

```
/**
 * @invariants OCLExpression
 */
```

Operators

```
/**
 * @preconditions  OCLExpression
 * @postconditions OCLExpression
 */
```

At most one may be present, connect multiple conditions with and**.**

Write constraints in `.java` file directly before feature they apply to.

Design by Contract

Pre-/postconditions like clauses in a contract about an operation

If the caller fulfills the precondition before the operation is called,

then the called object ensures the postcondition to hold after execution of the operation

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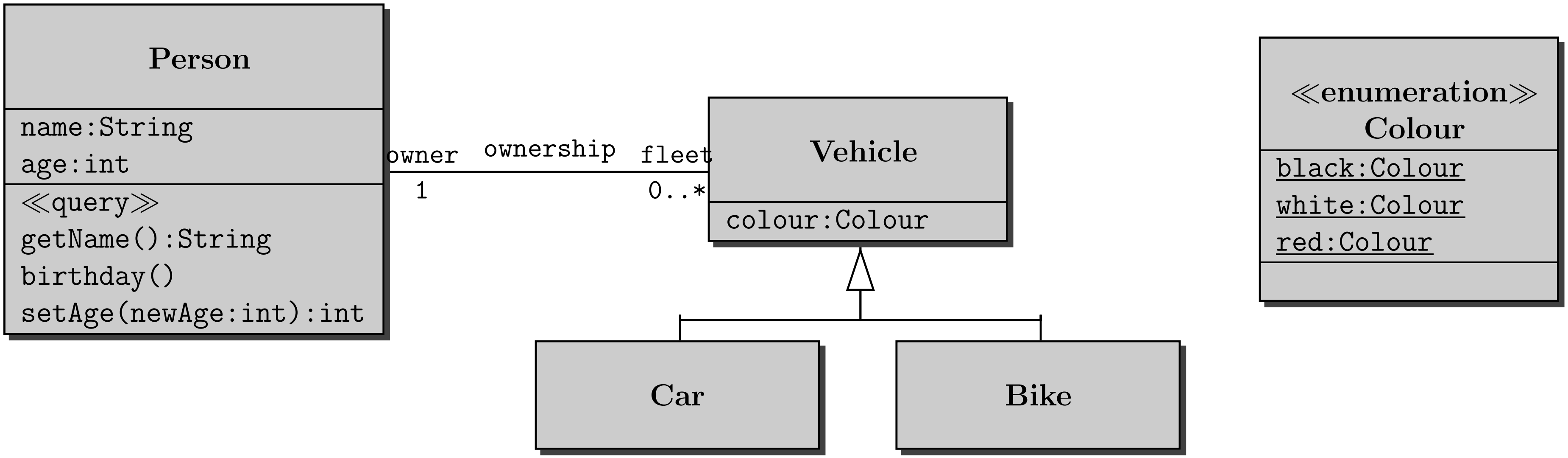
NOT

> **“Before executing an operation its precondition must hold”**

or

> **“Whenever the precondition holds, the operation is called”**

Constraints with Attributes



context **Person**

inv **: age** ≥ 18

Equivalent notational variations

context **Person**

inv **: self.age** ≥ 18

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context **Person**

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context **p:Person**

inv **: p.age** ≥ 18

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context **p:Person**

inv **minimumAge : p.age** ≥ 18

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context **Person**
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context **Person**
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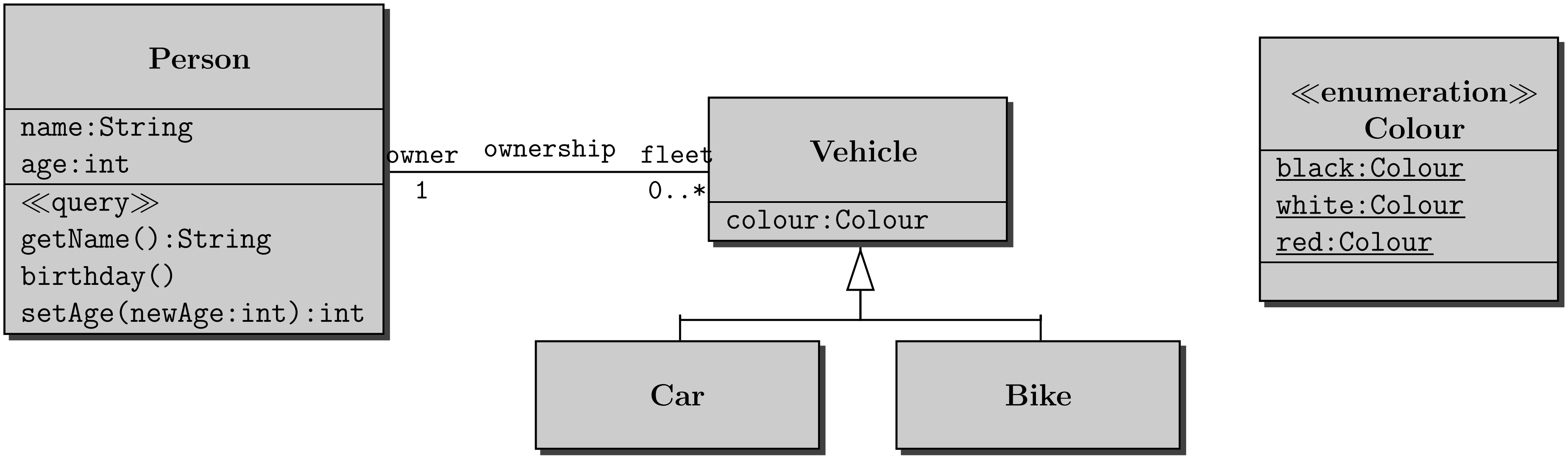
Beware: **variants using named instances not possible in Togther**

Operator Constraint: Contract



context **Person::setAge(newAge: int):int**

pre **: self.age ≥ 0 and newAge ≥ 0**

post **: self.age = newAge**

Which implementation satisfies the contract?

context **Person::setAge(newAge: int):int**

pre : **self.age** ≥ 0 **and newAge** ≥ 0

post : **self.age = newAge**

```
int setAge(int newAge) {
    if (age>=0 && newAge>=0) { this.age = newAge; }
    return this.age;
}
int setAge(int newAge) {
    return this.age = newAge;
}
int setAge(int newAge) {
    this.age = newAge;
    return -1;
}
```

OCL Types

UML class types

User-defined classes from context diagram of an OCL constraint

Each class of UML context diagram is legal type in OCL constraint

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Primitive types

$Integer$, $Real$, $Boolean$ **and** $String$ **(Together:** int, $real$, $boolean$**)**
int, $real$ **not in JAVA CARD, but** int, $short$, $byte$ **work in KeY**

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User-defined enumeration types (not supported in Together and KeY)

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Special types

e.g. $OclAny$, $OclType$

Type Conformance in OCL

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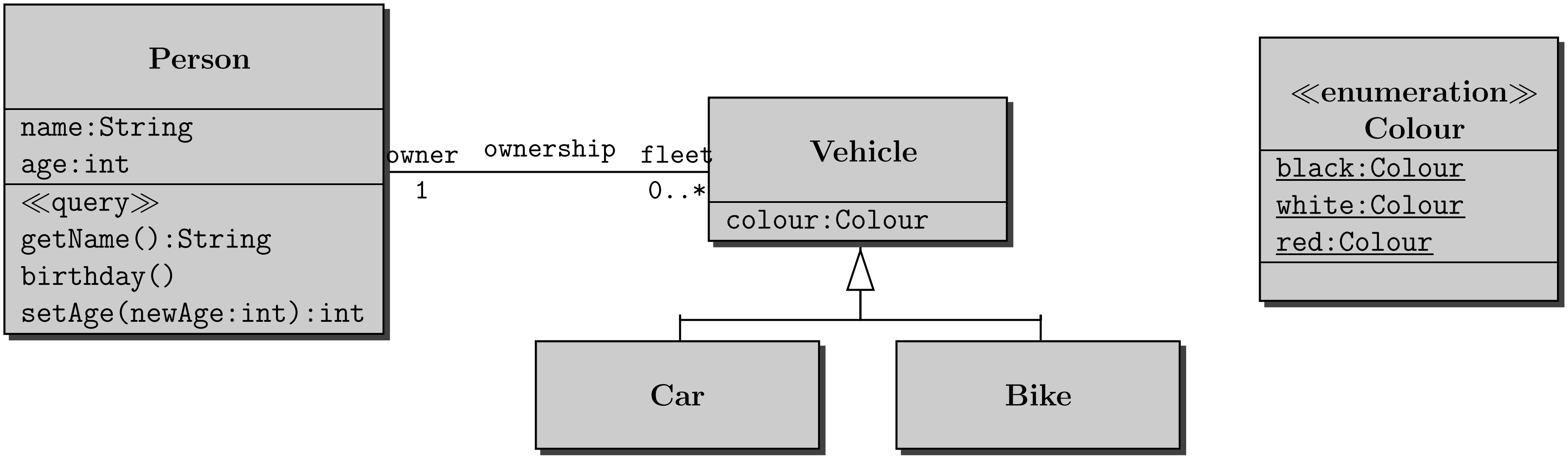
- **If** T **is not a collection type:** $T < OCLAny$
- **If** $T_1 < T_2$ **and** C **is any of the type constructors** $Collection$**,** Set**,** Bag**,** $Sequence$**:**

  $C(T_1) < C(T_2)$.

Typing Examples



context **Person** **- - self.name has type** $String$

- - self.age has type $Integer$

- - self.fleet has type $Set(Vehicle)$

context **Vehicle** **- - self.colour has type** $Colour$

context **...** **- - Colour.black has type** $Colour$

Navigation: Accessing Properties

OCL Properties (functions that may occur in OCL expr)

- **Attributes from underlying UML model**
- **Association ends from underlying UML model**
- **Operations with stereotype ≪query≫ from UML model**
- **Predefined OCL properties**

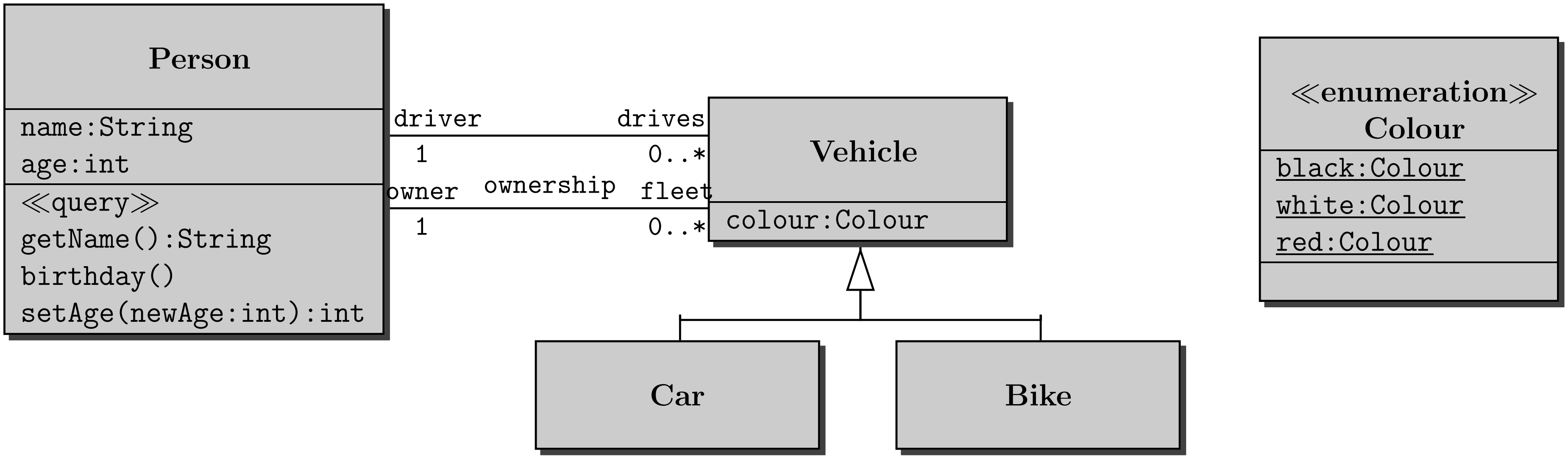
If argument has no collection type: dot notation (like JAVA)

If argument has collection type: arrow notation “–>”

Collection type has large number of predefined properties:

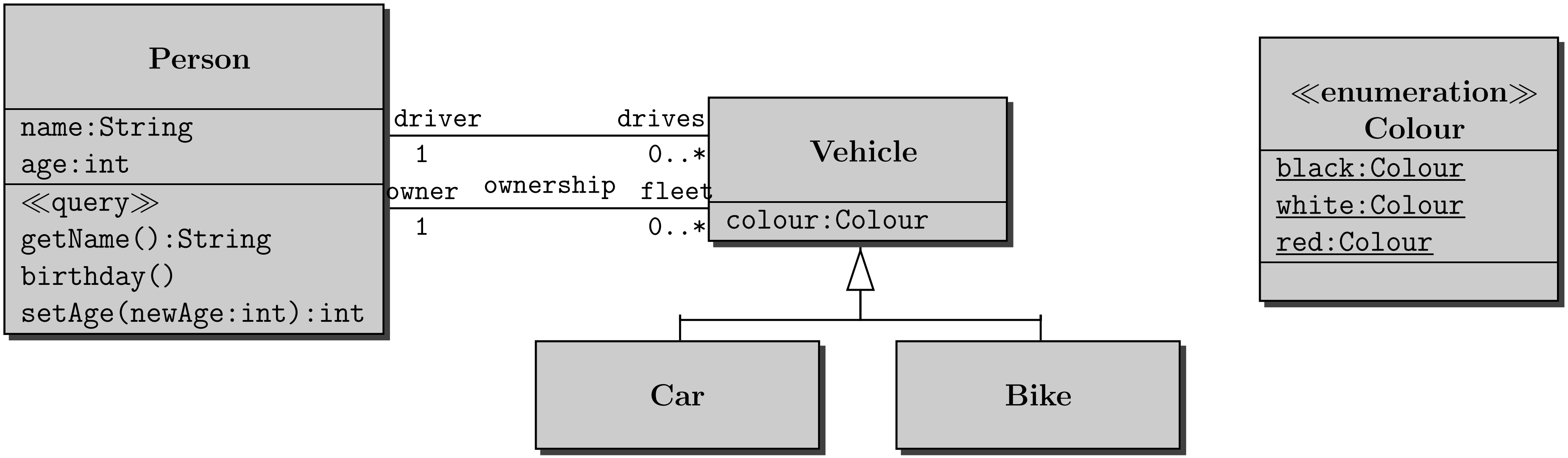
$\mathrm{includes}$, $\mathrm{intersection}$, forAll, **etc.**

User-Defined Operations within Constraints



Only «query» operations allowed to occur within OCL expressions

User-Defined Operations within Constraints



Only ≪query≫ operations allowed to occur within OCL expressions

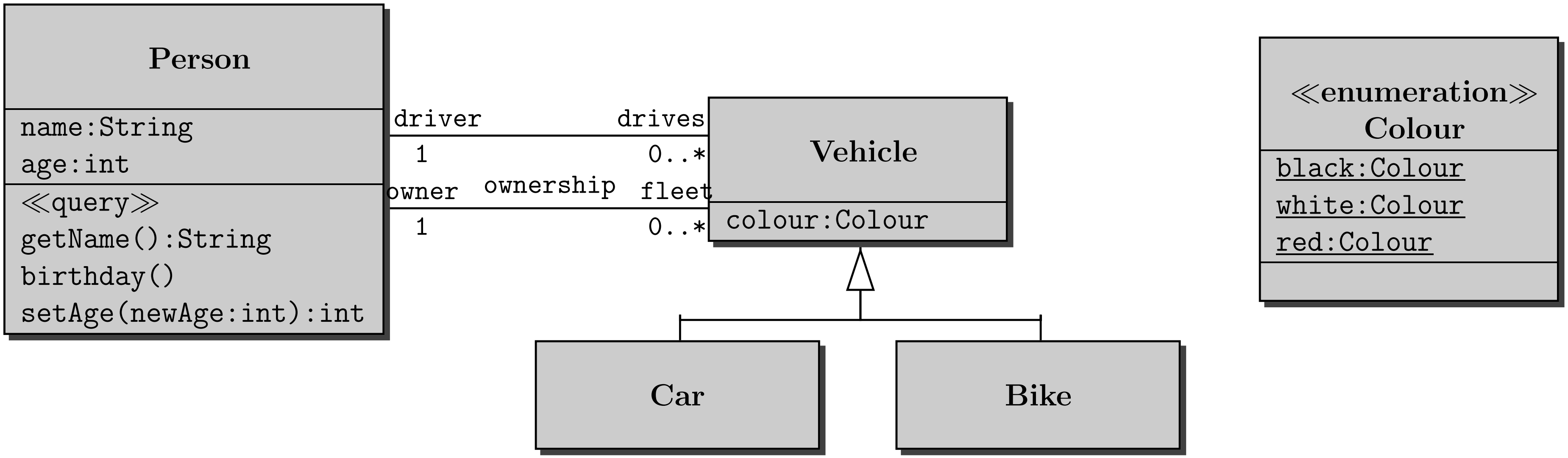
context **Person**

  inv **self.name = self.getName()**

Beware: parameterless properties with brackets, eg:

Set$\{1, 2, 3\}$ **–>** **sum()**

Constraints that use Associations



context **Vehicle**

inv **owner <> driver** **- - 'self' implicit!**

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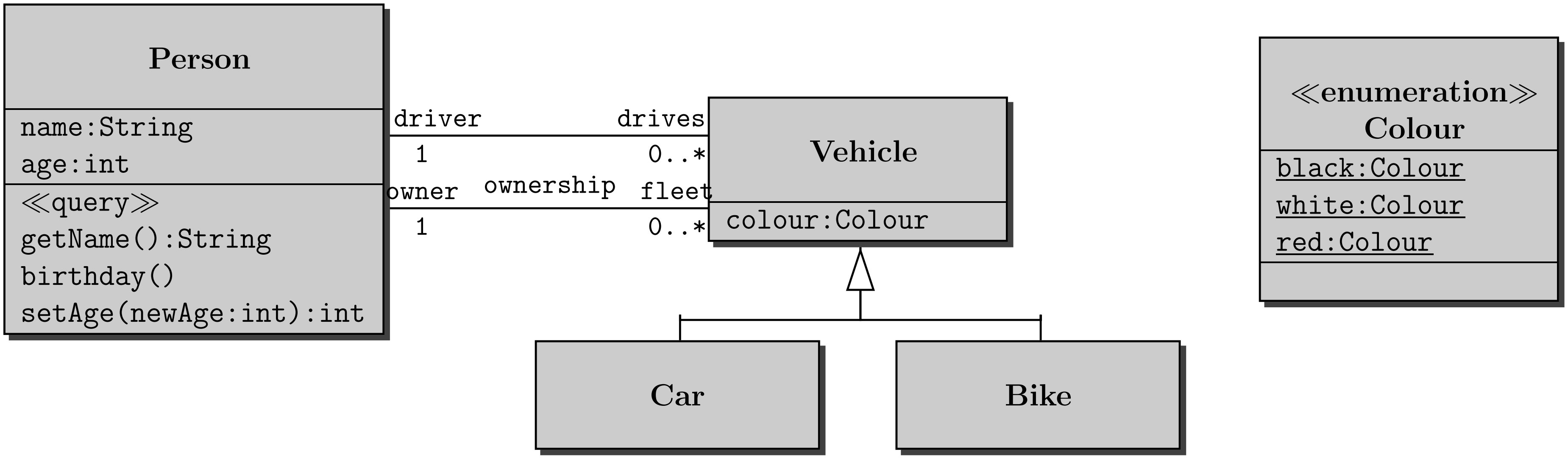


context **Vehicle**

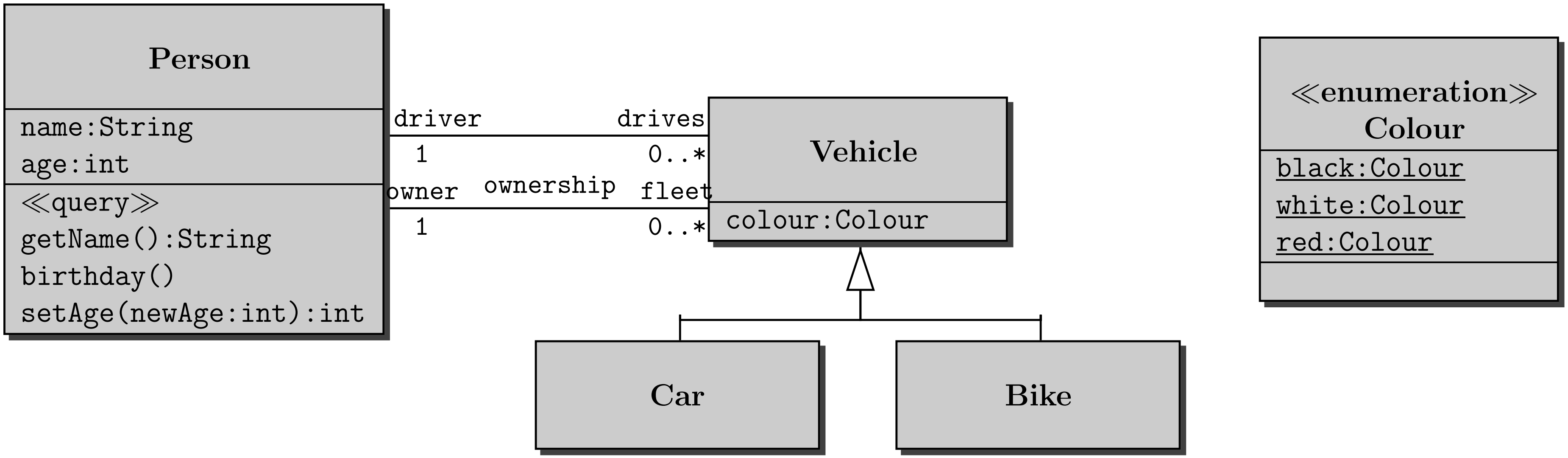
inv **owner <> driver** **- - 'self' implicit!**

context **Person**

inv **fleet –>intersection(drives) –>isEmpty()**

inv **self.fleet –>intersection(self.drives) –>isEmpty()**

Notational Variants of Collection Properties



context **Person** - - all constraints are equivalent

inv **fleet –>collect(v:Vehicle | v.colour) –>size() = 1**

inv **fleet –>collect(v | v.colour) –>size() = 1**

inv **fleet –>collect(colour) –>size() = 1**

inv **fleet.colour –>size() = 1** - - shorthand for 'collect' in Together

The type OclType

What is the type of UML model types (eg, Person**)?**

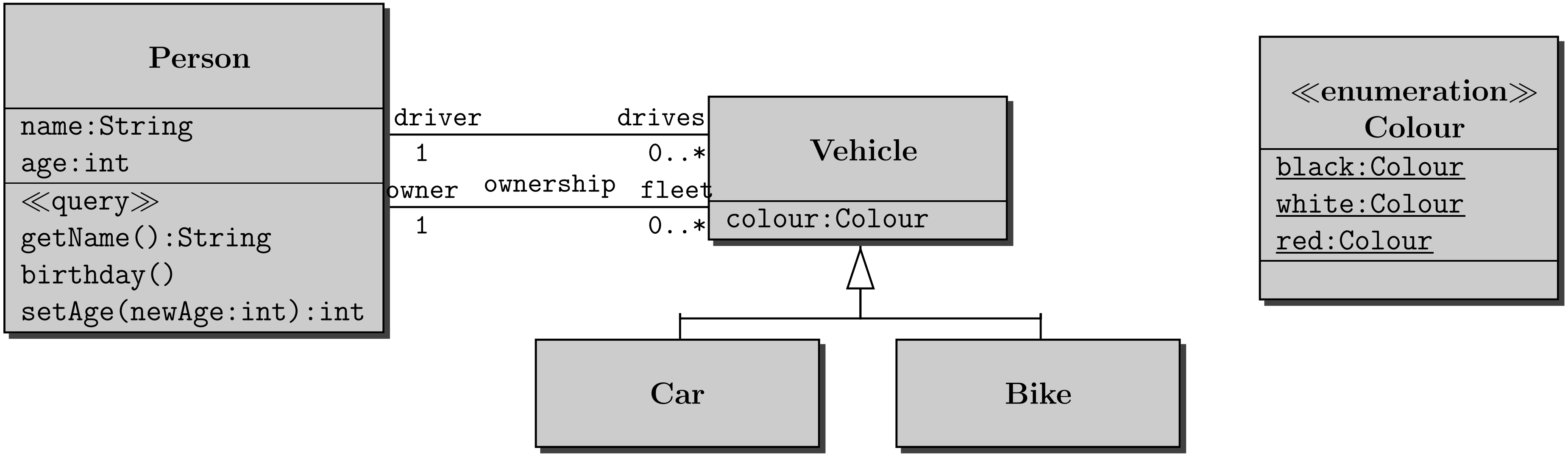
OclType

OclType **is metatype with predefined properties:**

- aType**.name() gives name string of** aType
- **Similar are attributes(), operations(), associationEnds()**
- aType**.allInstances() gives all instances of** aType **in current snapshot**

allInstances **needed to express properties relating to all currently existing objects**

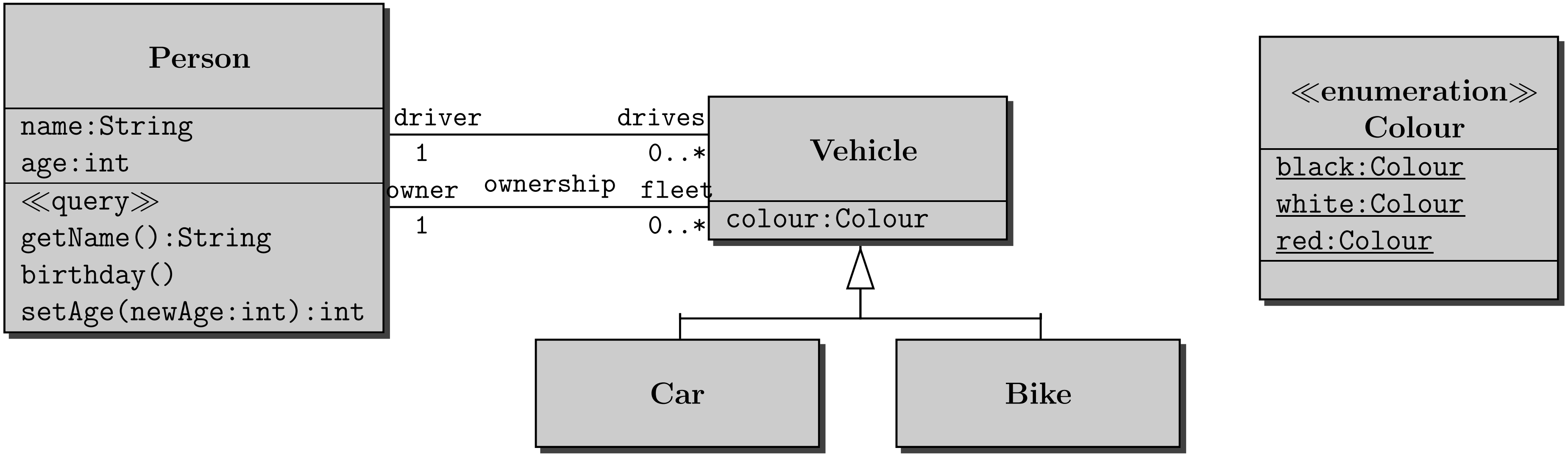
Using allInstances



context **Person**

inv **Person.allInstances –> forAll(p | p.age $\geq$ 0)**

Using allInstances



context **Person**

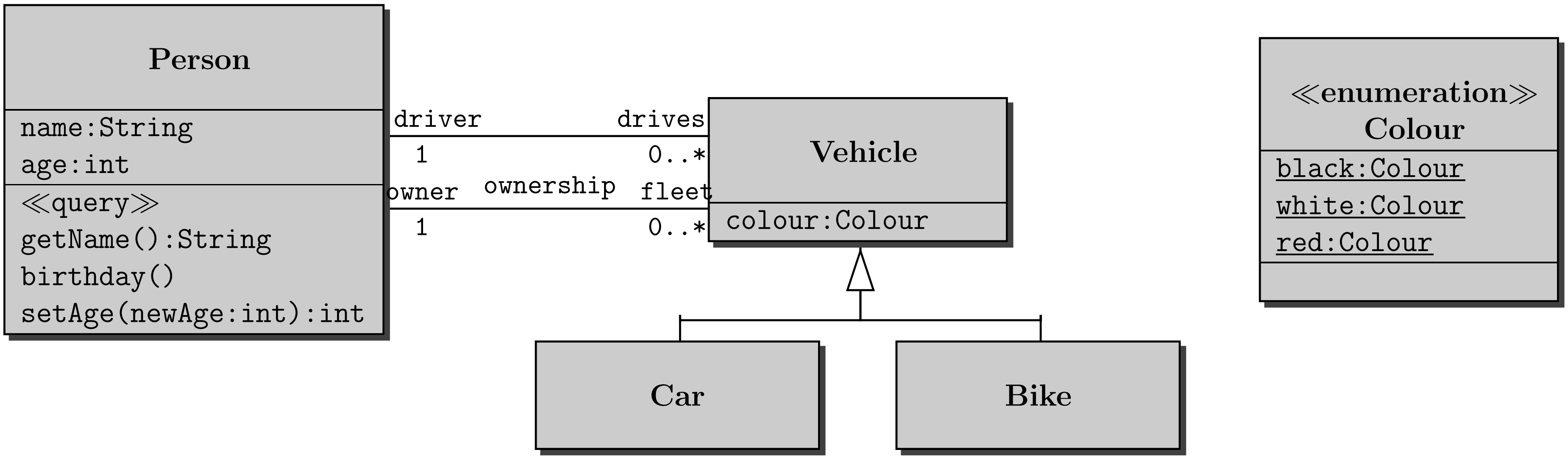
inv **Person.allInstances –> forAll(p | p.age ≥ 0)**

Constraint is independent of model context — equivalent:

context **Vehicle**

inv **Person.allInstances –> forAll(p | p.age ≥ 0)**

Using allInstances



context **Person**

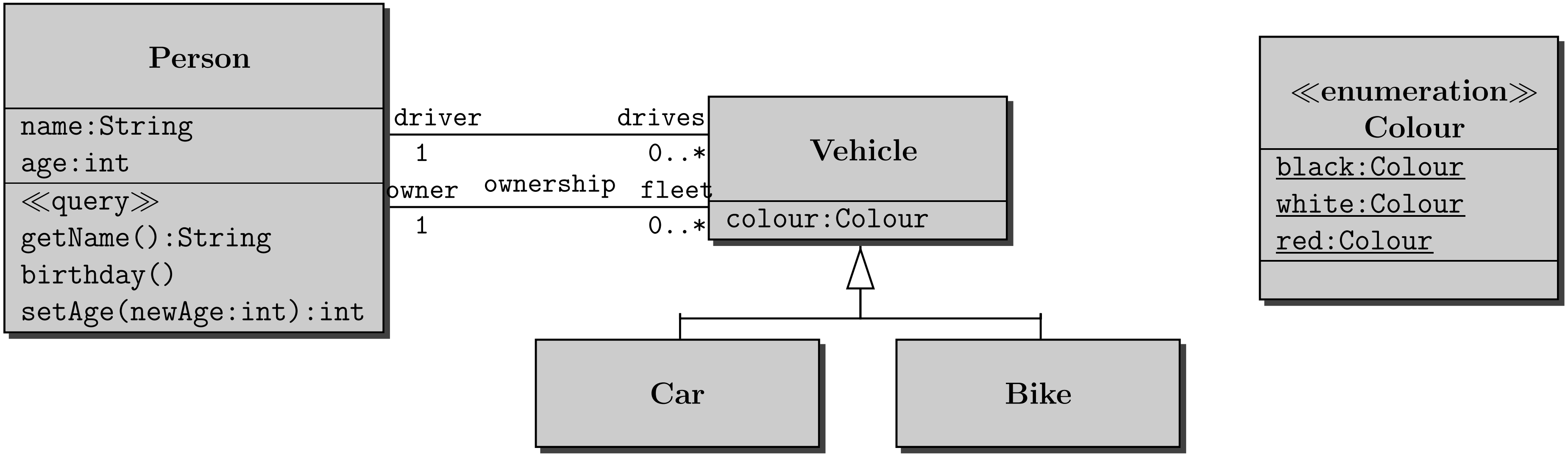
inv **Person.allInstances –> forAll(p | p.age $\geq$ 0)**

Context declaration of invariant has implicit allInstances/forAll:

context **Person** **- - equivalent to constraint above**

inv **self.age $\geq$ 0**

Avoiding allInstances



context **Person**

inv **Person.allInstances –>**

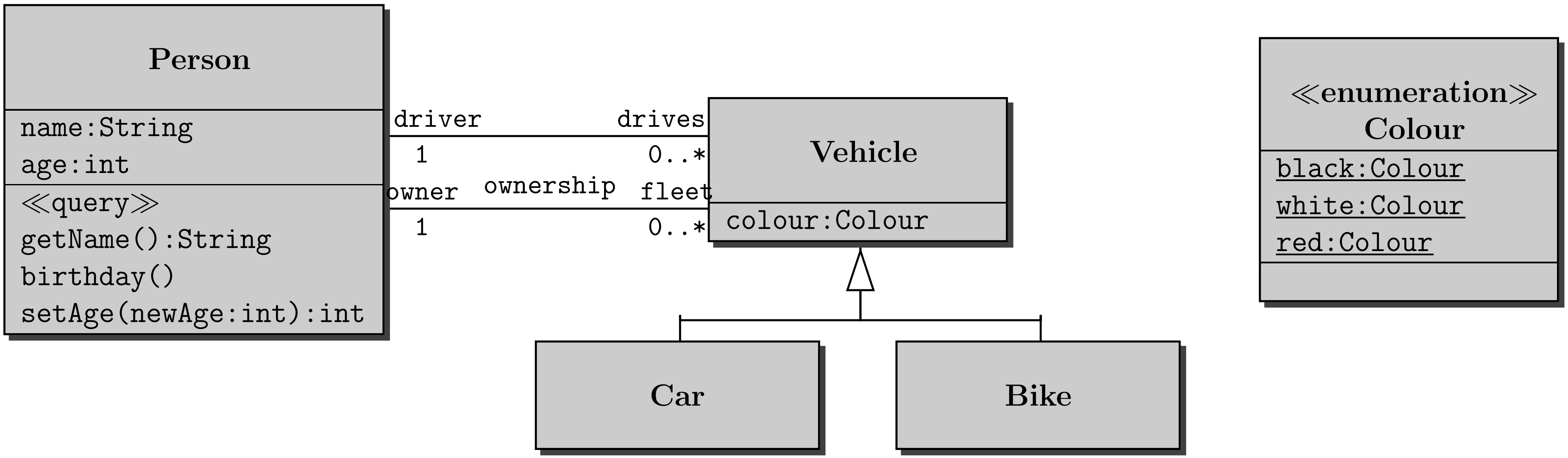
forAll(p1, p2 | p1.name = p2.name implies p1 = p2)

allInstances

. . . tends to make constraint difficult to read

. . . can give rise to unnecessarily difficult verification task

Avoiding allInstances



context **Person**

inv **Person.allInstances –>**

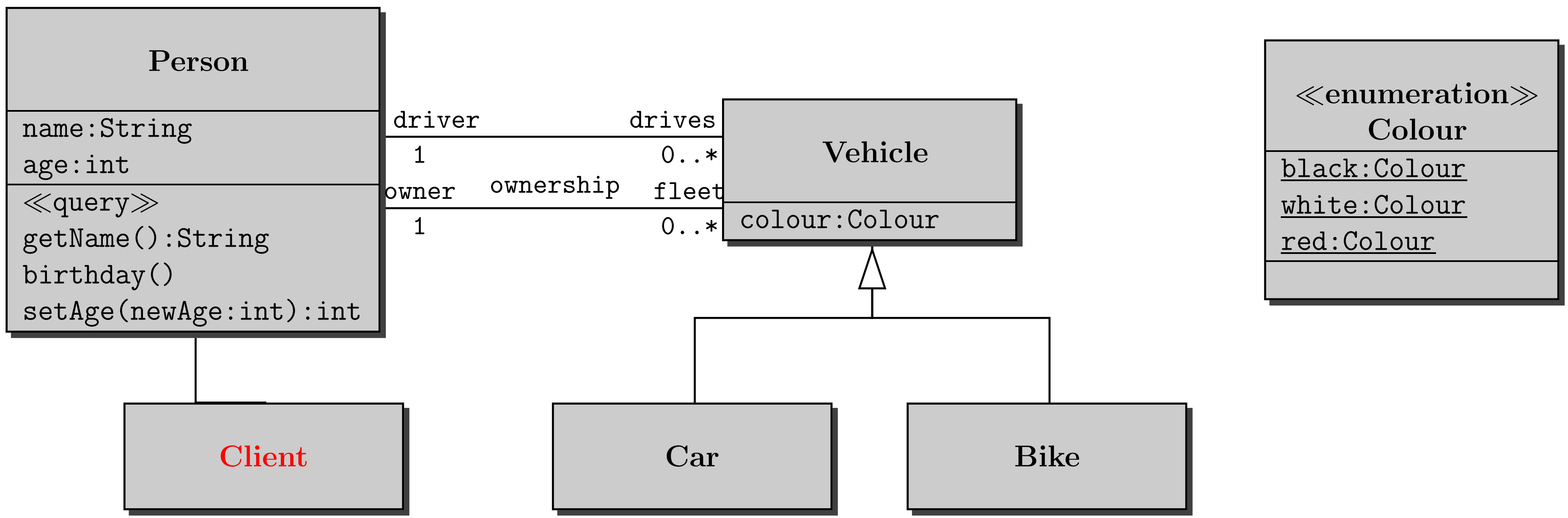
forAll(p1, p2 | p1.name = p2.name implies p1 = p2)

Can be equivalently replaced with: (not in Together!)

context **p1,p2:Person**

inv **p1.name = p2.name implies p1 = p2**

Avoiding allInstances



context **Person**

inv **Person.allInstances –>**

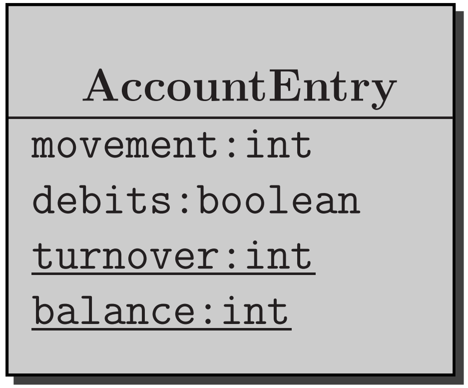
forAll(p1, p2 | p1.name = p2.name implies p1 = p2)

Often, collection of objects available via suitable association:

context **Client**

inv **: person –> forAll(p1, p2 | p1.name = p2.name implies p1 = p2)**

The iterate Property



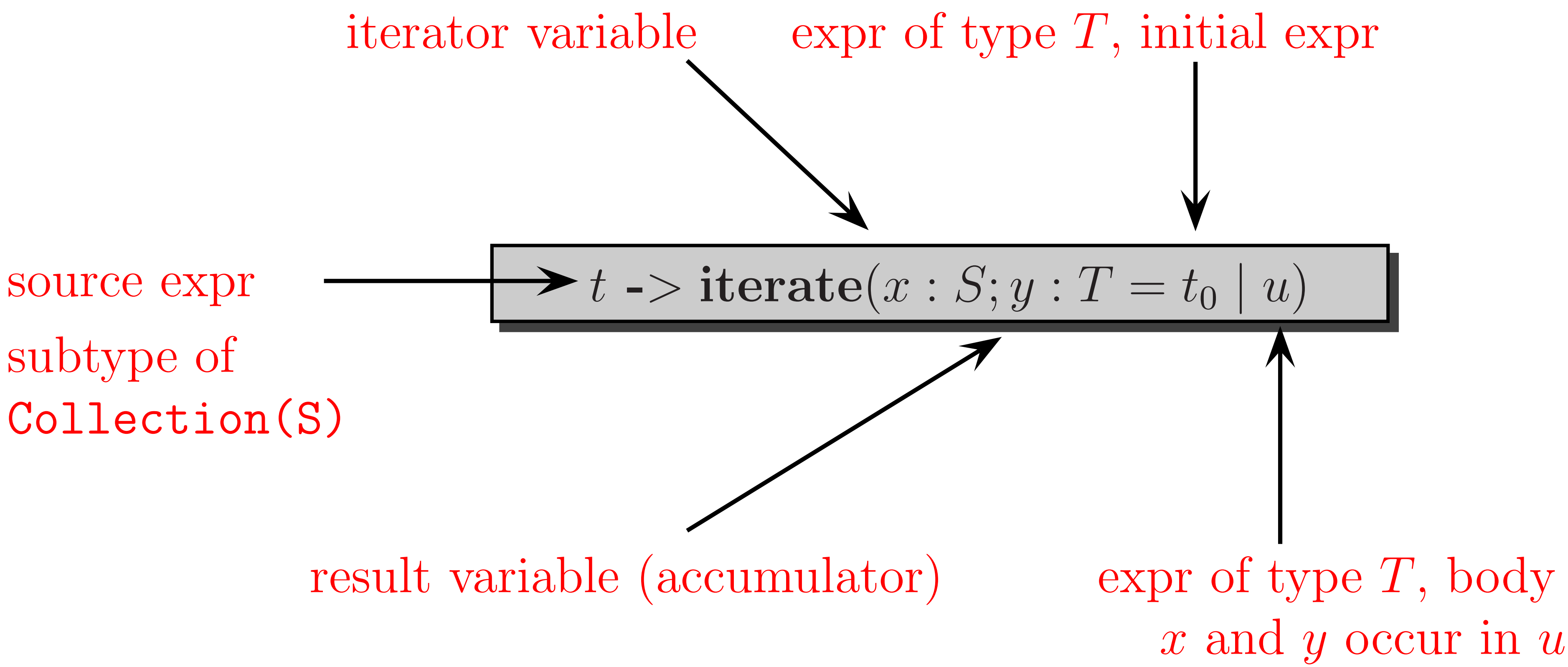
context **AccountEntry**

inv **AccountEntry.allInstances –>**

iterate(a:AccountEntry ; m:Integer=0 | m+a.movement) =

AccountEntry.turnover

Syntax of the *iterate* Property



Java Pseudocode of *iterate*

t –>iterate(x:S; y:T=t_0 | u)

```
S x;
T y = t0;
for (Enumeration e = t.elements(); e.hasMoreElements() ) {
  x = e.nextElement();
  y = u(x,y);
}
```

Type of x and y can be inferred from t and u

OCL's iterate is also similar to the accumulate function of the C++ STL

Quantifiers

t –>iterate(x:S; y:Boolean=true | y and a(x))

. . . **where** $a(x)$ **is an expression of type** $\mathrm{Boolean}$ **(with occurrence of** x**)**

Quantifiers

$$\text{t ->iterate(x:S; y:Boolean=true} \mid \text{y and a(x))}$$

. . . where $a(x)$ is an expression of type $\mathrm{Boolean}$ (with occurrence of x)

Can be equivalently expressed by

$$\text{t ->forAll(x} \mid \text{a(x))}$$

Quantifiers

t –>iterate(x:S; y:Boolean=true | y and a(x))

. . . where $\mathrm{a(x)}$ **is an expression of type** $\mathrm{Boolean}$ **(with occurrence of** x**)**

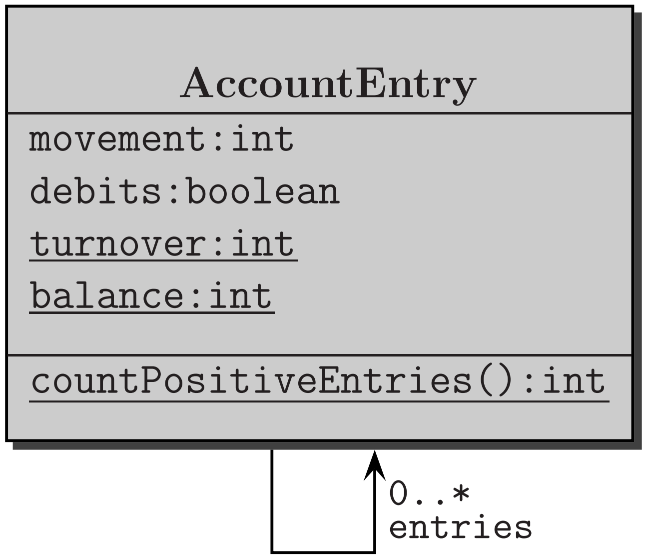
Can be equivalently expressed by

t –>forAll(x | a(x))

Similar:

t –>exists(x | a)

Selecting Elements

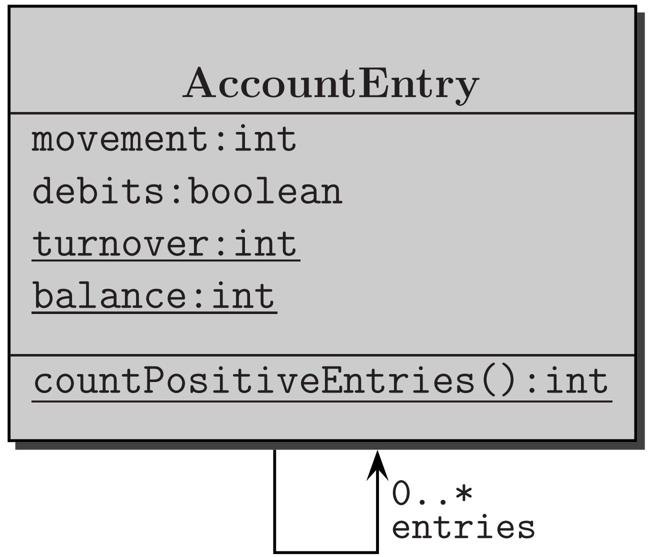


context **AccountEntry::countPositiveEntries():int**

pre **: true**

post **: result = AccountEntry.allInstances –>**
select(e | not e.debits) –> size()

Selecting Elements



context **AccountEntry::countPositiveEntries():int**

pre : **true**
post : **result = AccountEntry.allInstances –> select(e | not e.debits) –> size()**

Alternative notation using self-association:

post : **result = entries –> select(not debits) –> size()**

Reducing *select* to *iterate*

Like all other collection properties *select* definable with *iterate*

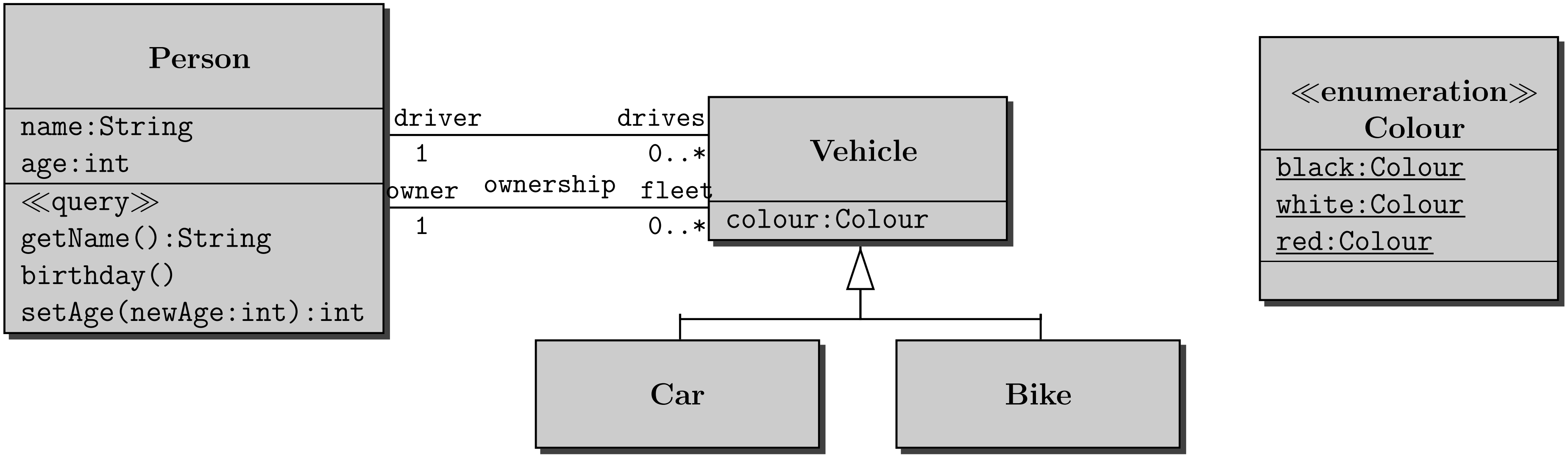
s –> select(x:T | e) =

iterate(x:T; acc: Set(T) = Set{} |

if e then acc –> including(x) else acc)

- s **is of type** $Set(T)$
- e **is an OCL expression of type** Boolean
- including **in turn is definable with** iterate
- **all built-in collection properties definable with** iterate **and** includes

Referring to Previous Values



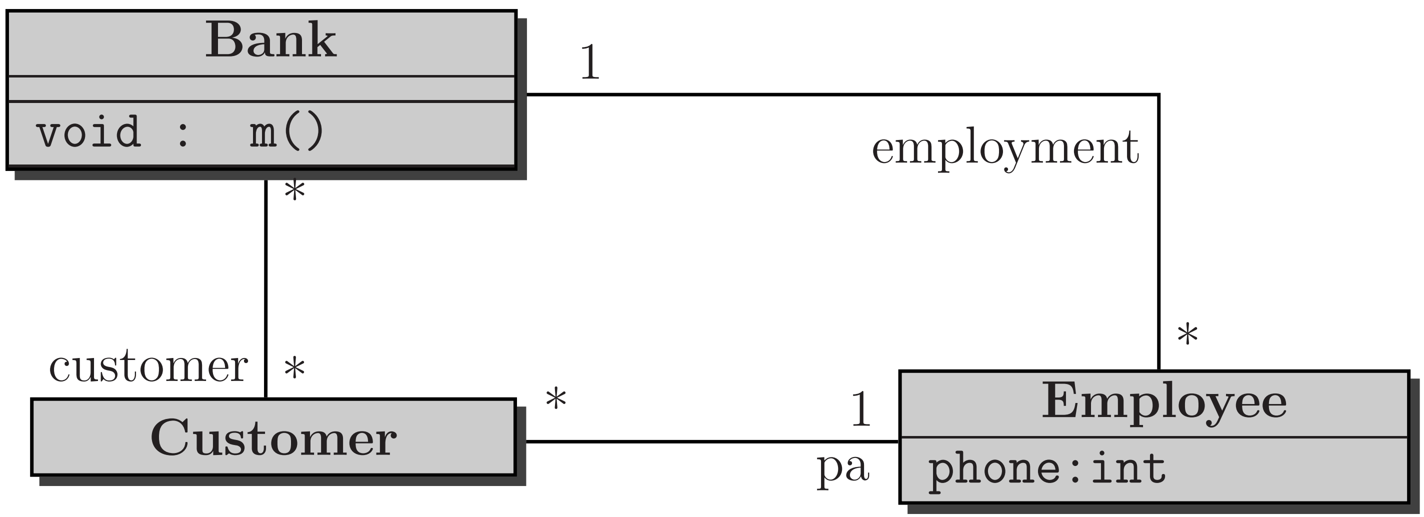
context **Person::birthday()**

pre **age $\geq$ 0**

post **age = age@pre + 1**

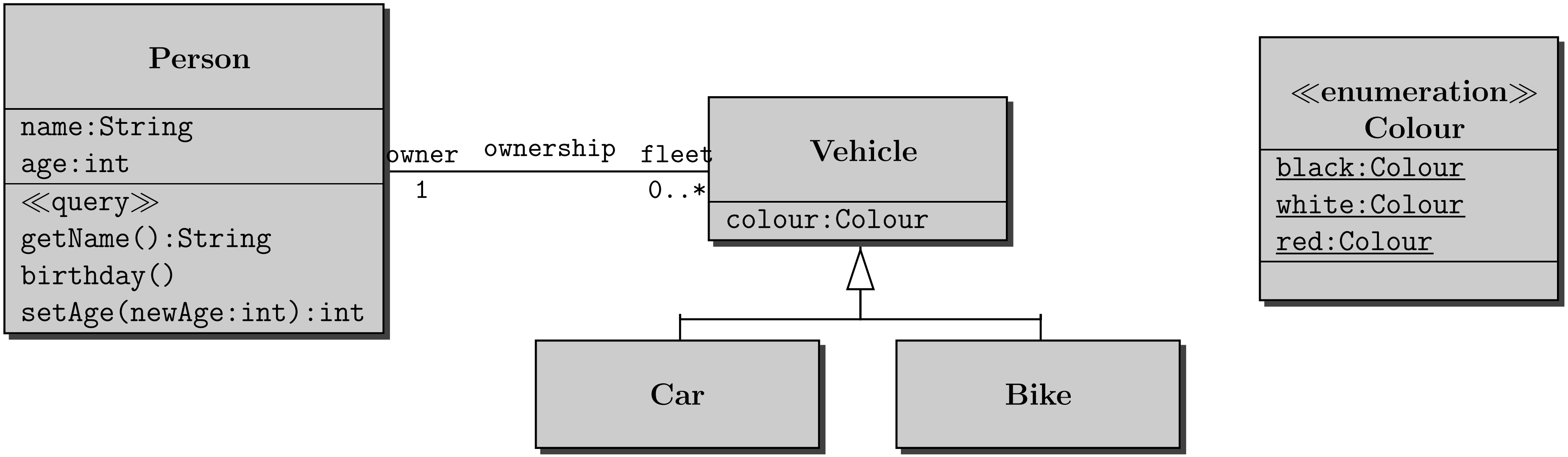
User-defined properties qualified with @pre refer to value in prestate

Multiple Occurrences of @pre



$aCustomer.pa.phone$	**new phone number of current p.a.**
$aCustomer.pa@pre.phone$	**new phone number of previous p.a.**
$aCustomer.pa.phone@pre$	**old phone number of current p.a.**
$aCustomer.pa@pre.phone@pre$	**old phone number of previous p.a.**

A Method Does More Than It Should



context **Person::setAge(newAge: int):int**

pre : **self.age** ≥ 0 **and newAge** ≥ 0

post : **self.age = newAge**

```
int setAge(int newAge) { // correct implementation?!
    name = "Jabberwocky";
    return this.age = newAge;
}
```

The Frame Problem

How to express that nothing else is changed than what is specified?

Known in AI as the Frame Problem

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First Solution

context **Person::setAge(newAge: int):int**

pre : **self.age** ≥ 0 **and newAge** ≥ 0

post : **self.age = newAge and name = name@pre**

Done for all attributes visible for context class: very tedious!

The Frame Problem

How to express that nothing else is changed than what is specified?

Known in AI as the Frame Problem

Second Solution

context **Person::setAge(newAge: int):int**

pre : **self.age** ≥ 0 **and newAge** ≥ 0

post : **self.age = newAge**

modifies: **self.age**

The OCL to FOL compiler creates an efficient representation

KeY extension to OCL, not in the standard

Snapshots and OCL Constraints

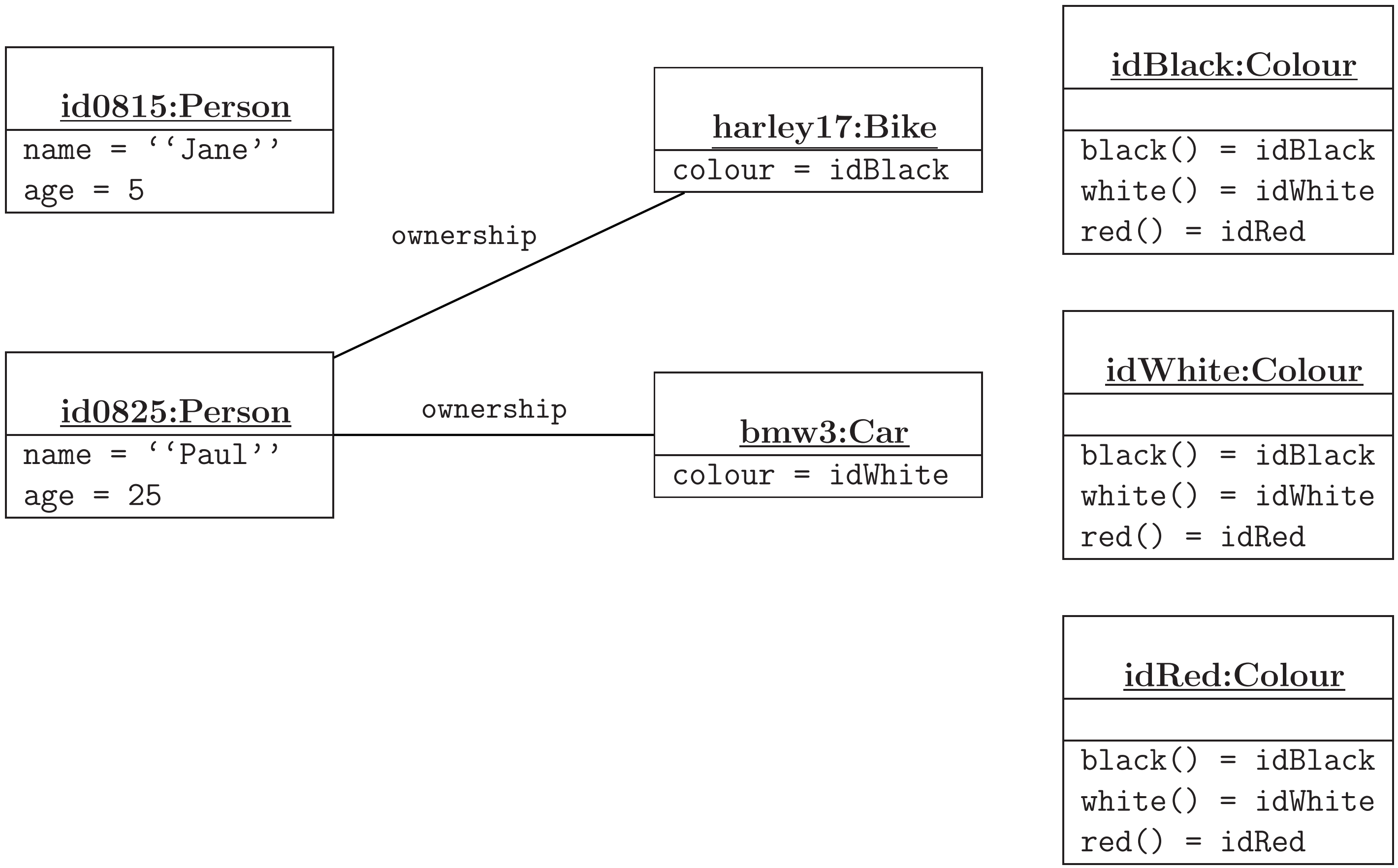
- **OCL constraints evaluated relative to a snapshot I**

  (Recall that snapshot determines an object diagram)
- **OCL expressions have type $\mathrm{Boolean} \Rightarrow$ they are true or false wrt I**
- **OCL constraints restrict legal snapshots of UML diagram**

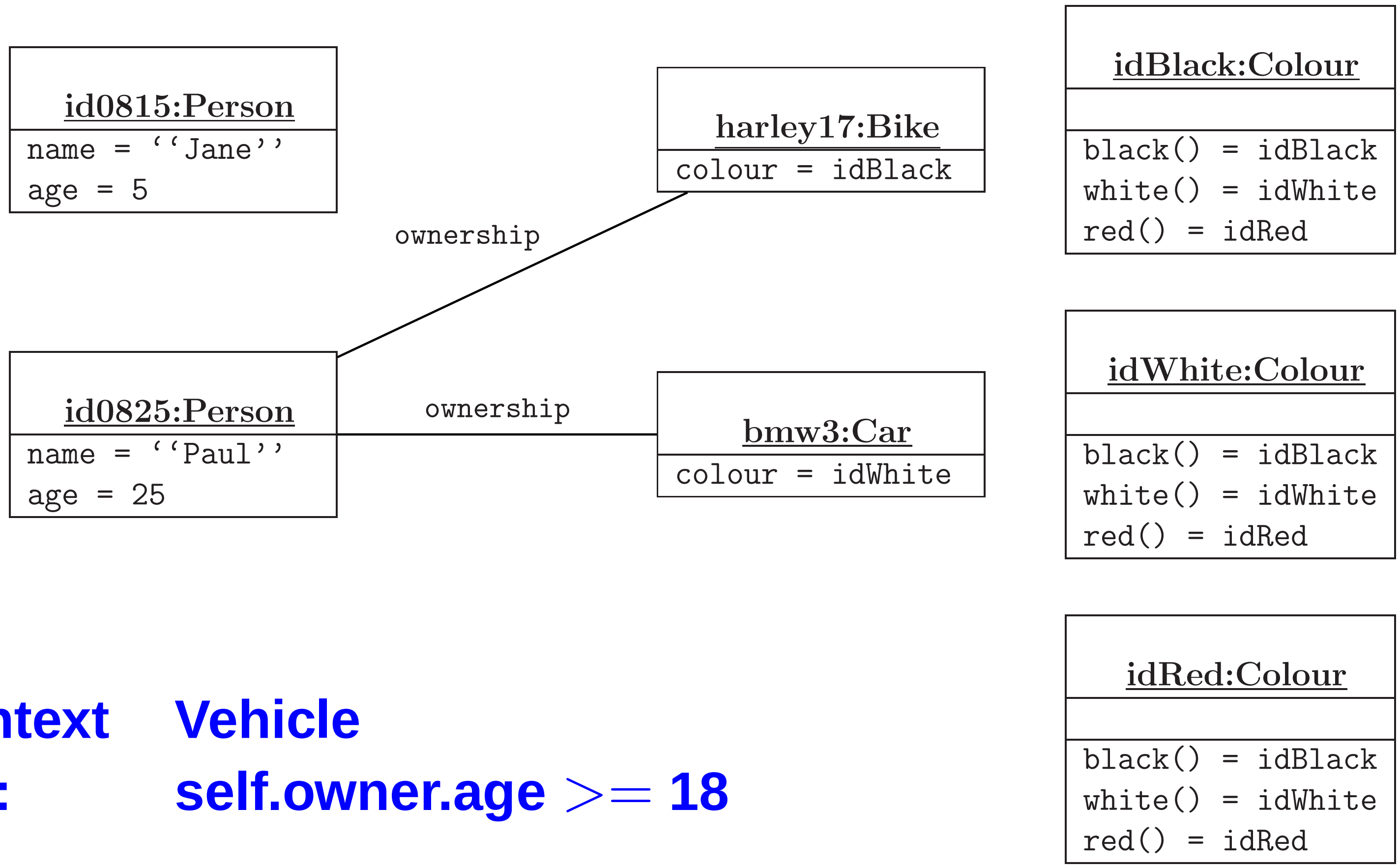
  Possibility to express intended semantics of diagram
- **OCL expressions can be evaluated and checked wrt given snapshot**
- **Don’t give formal semantics of OCL in terms of snapshots**

  Tell later how UML/OCL is translated into FOL/DL

Object Diagrams and OCL Constraints

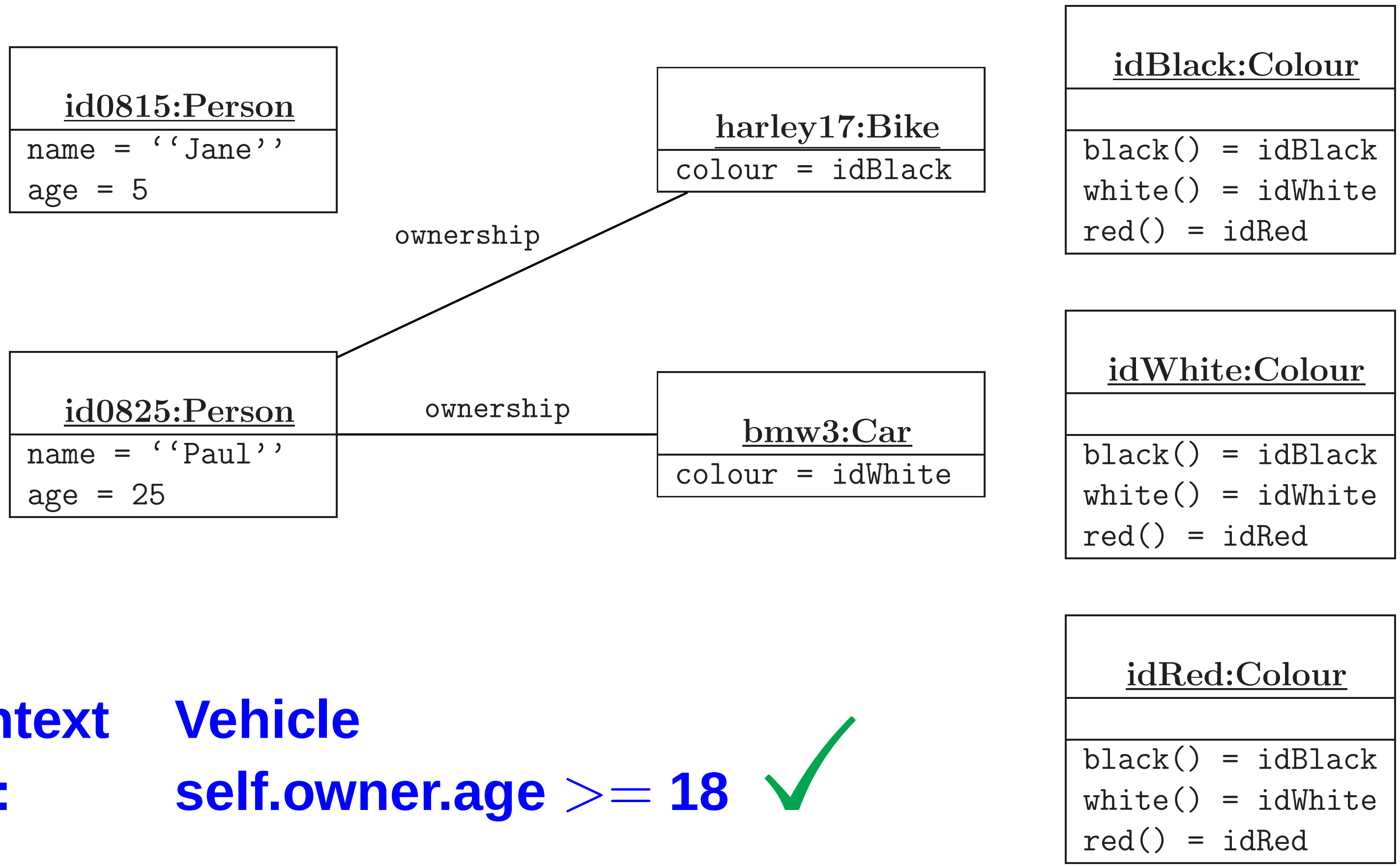


Object Diagrams and OCL Constraints



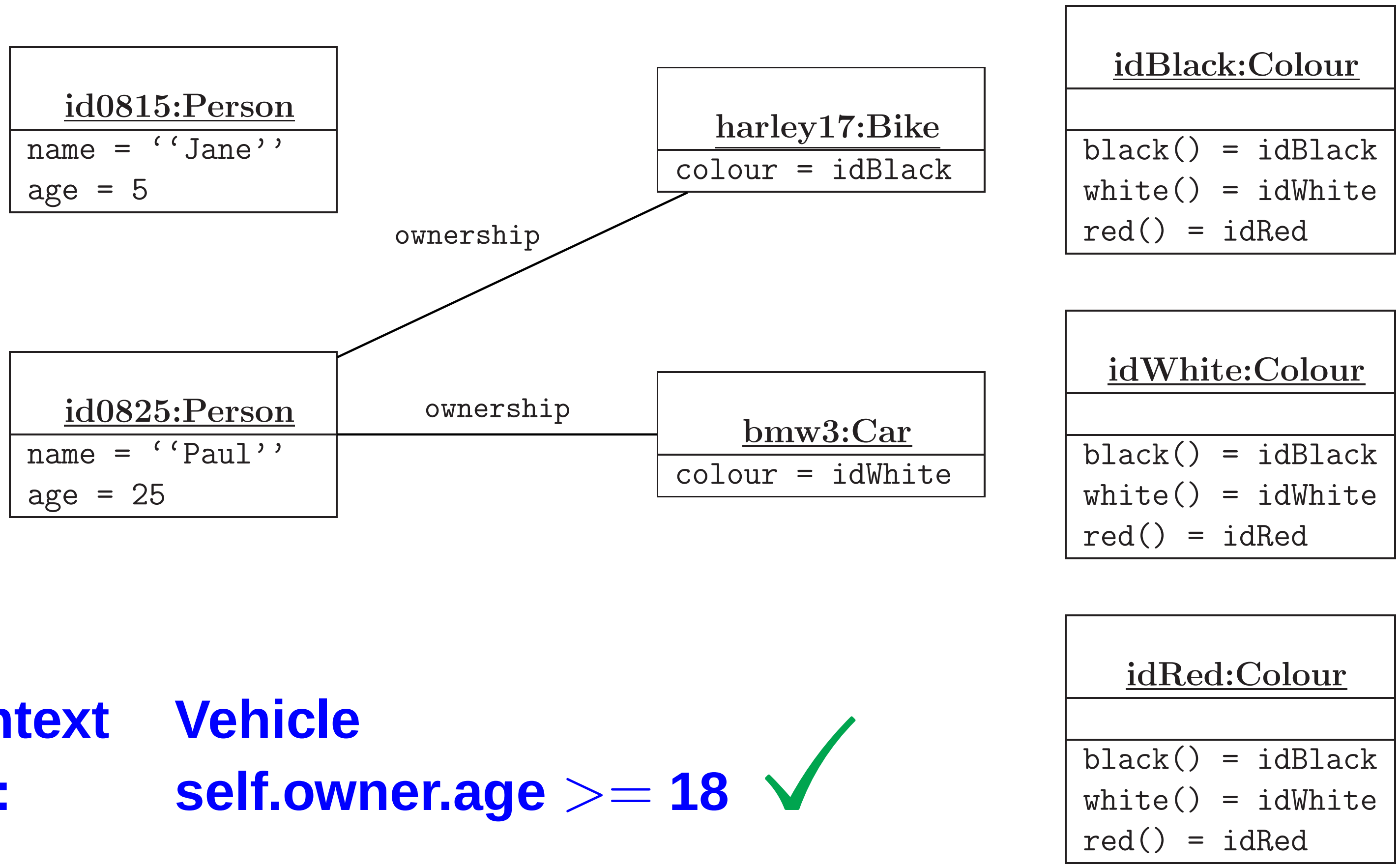
context **Vehicle**
inv: **self.owner.age $>=$ 18**

Object Diagrams and OCL Constraints



context Vehicle
inv: self.owner.age $>=$ 18 ✓

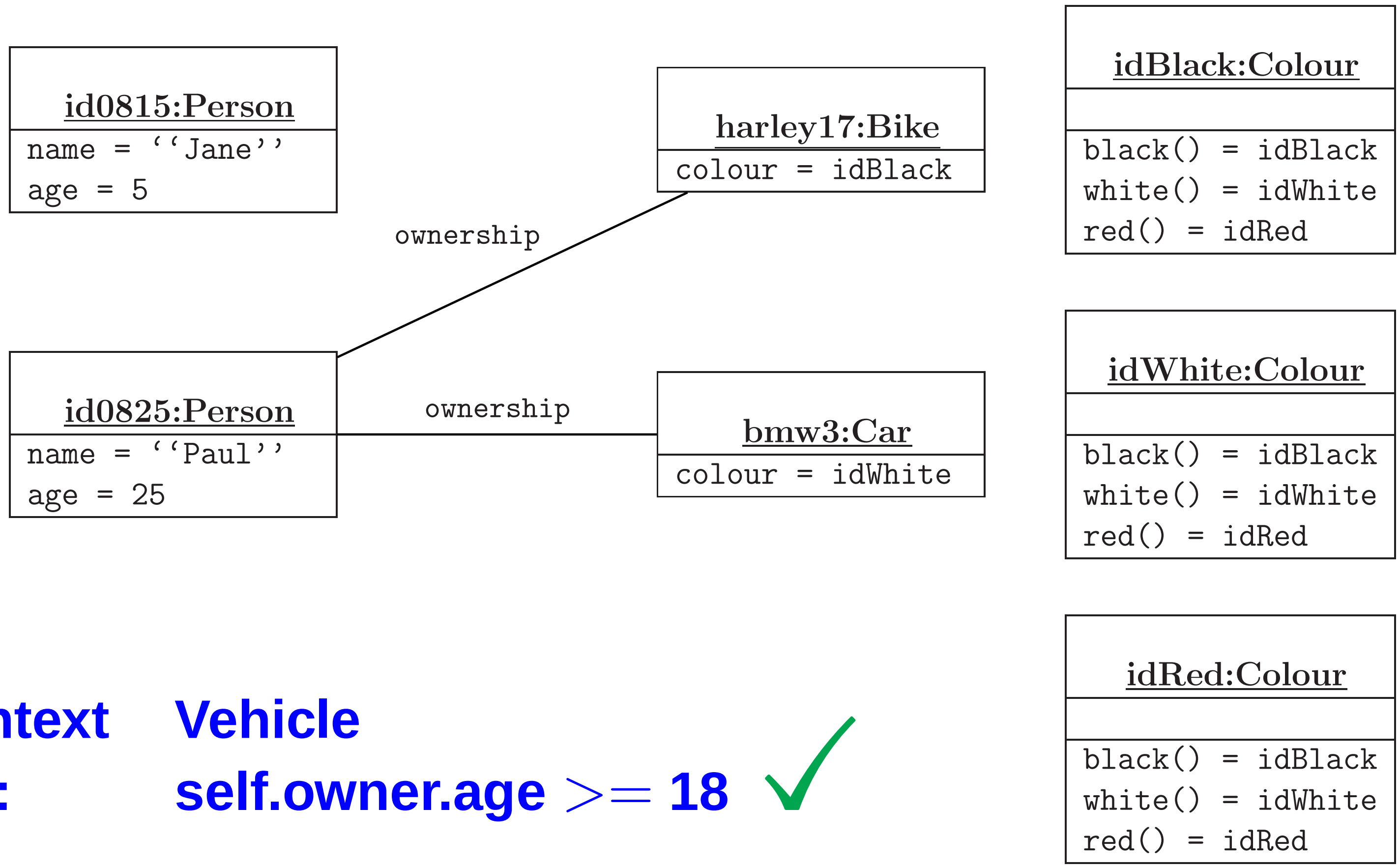
Object Diagrams and OCL Constraints



context **Vehicle**
inv: **self.owner.age $>=$ 18** ✓

context **Person**
inv: **fleet–$>$forAll(colour = Colour.black)**

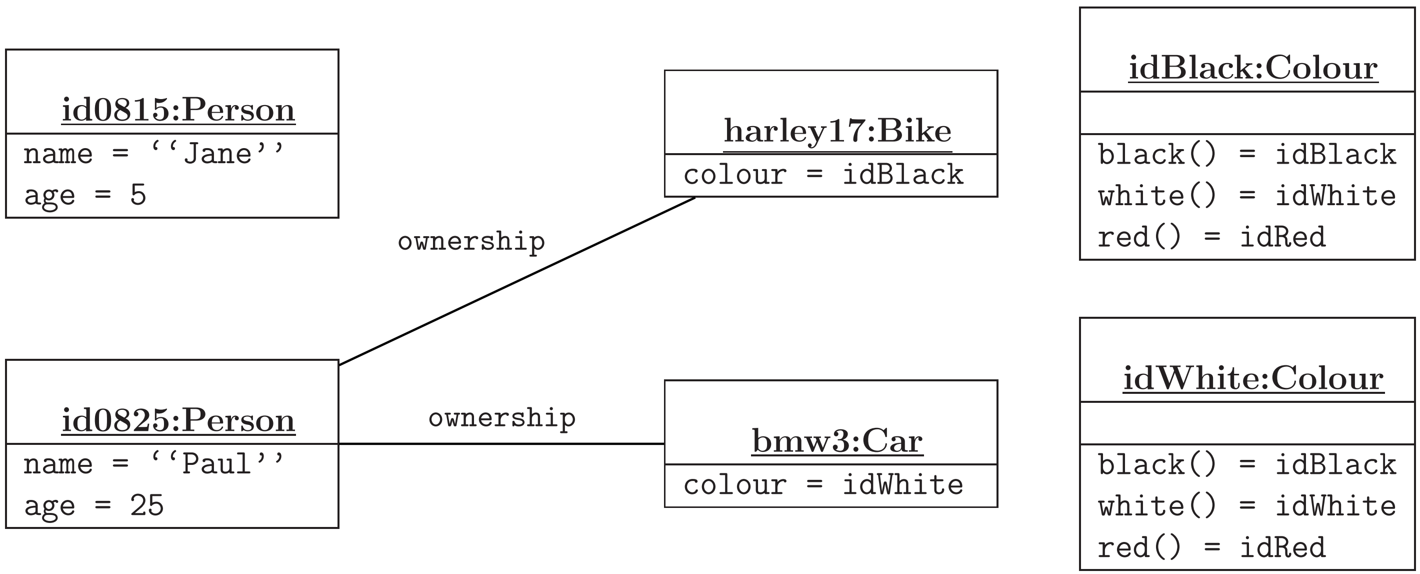
Object Diagrams and OCL Constraints

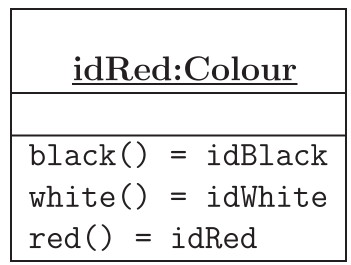


context **Vehicle**
inv: **self.owner.age >= 18** ✓

context **Person**
inv: **fleet–>forAll(colour = Colour.black)** ☒

Object Diagrams and OCL Constraints





context **Vehicle**

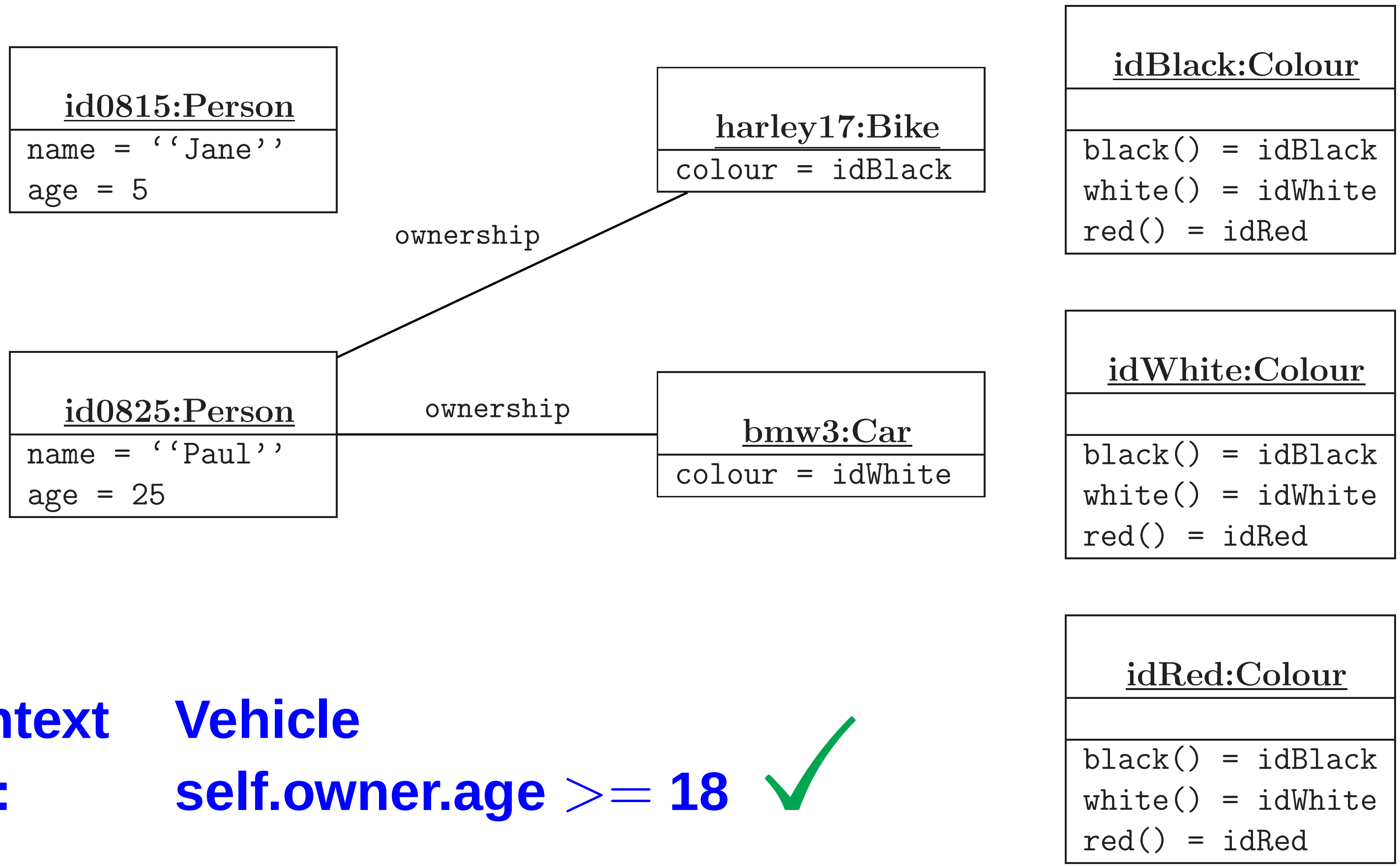
inv: **self.owner.age >= 18** ✓

context **Person**

inv: **fleet–>forAll(colour = Colour.black)** ☒

inv: **fleet–>select(colour = Colour.black) –>size() <= 3**

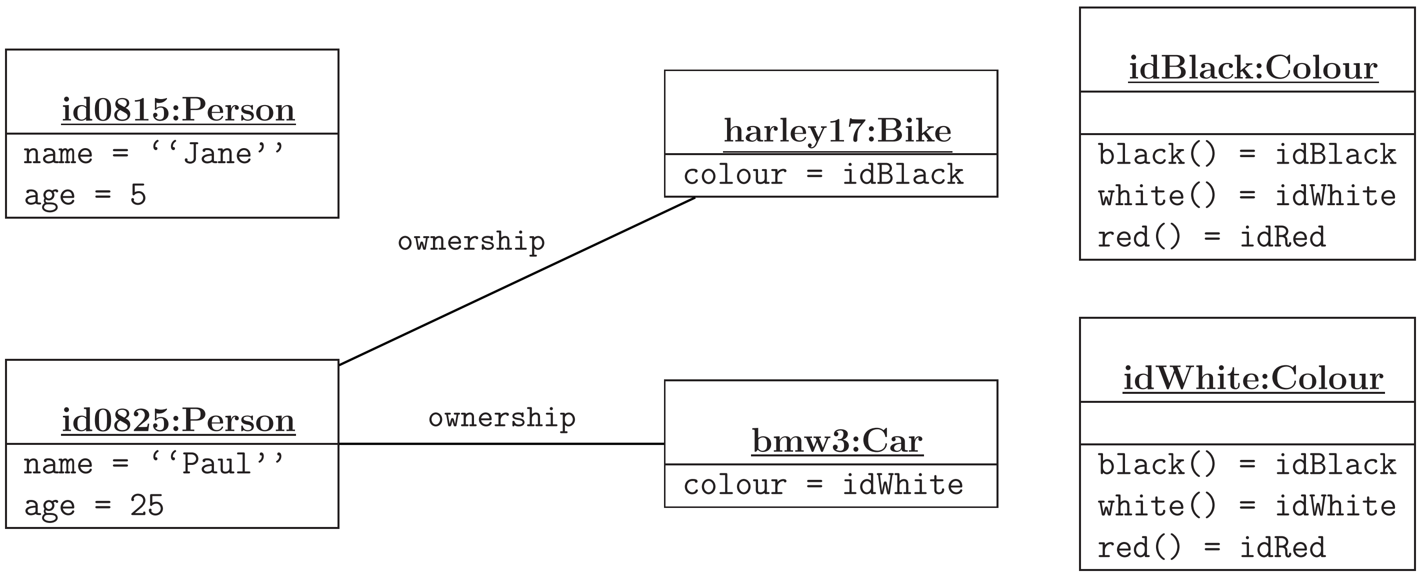
Object Diagrams and OCL Constraints

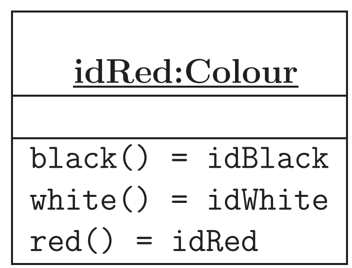


context **Vehicle**
inv: **self.owner.age >= 18** ✓

context **Person**
inv: **fleet–>forAll(colour = Colour.black)** ☒
inv: **fleet–>select(colour = Colour.black) –>size() <= 3** ✓

Object Diagrams and OCL Constraints





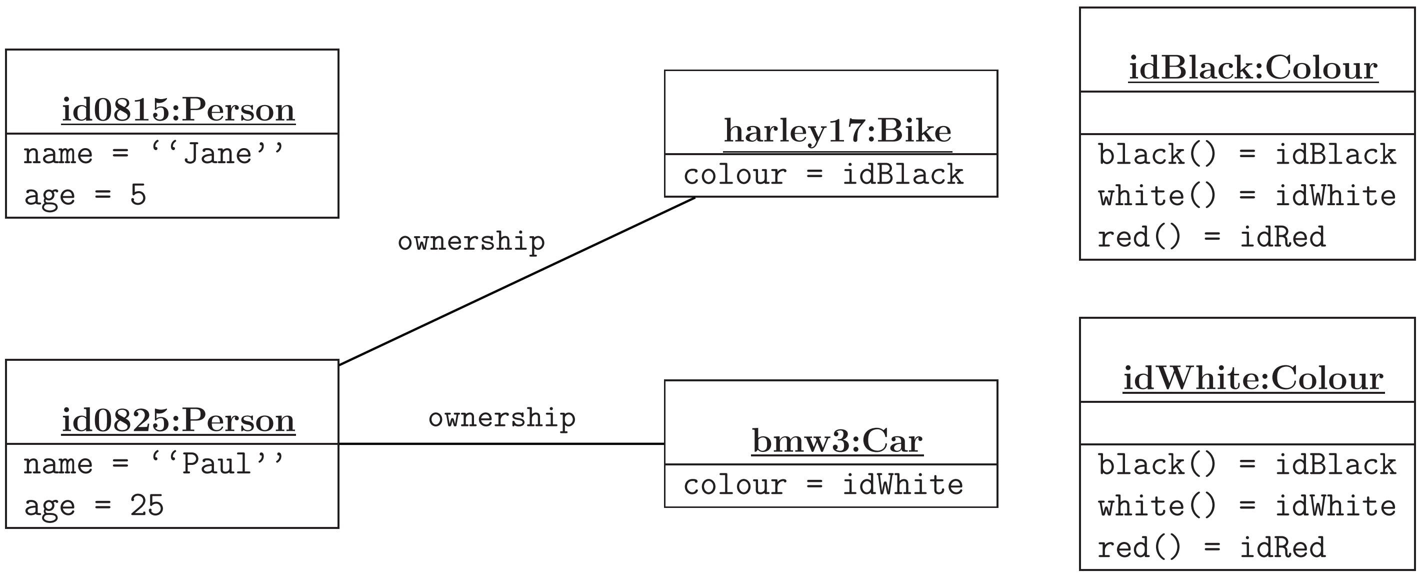
context **Vehicle**
inv: **self.owner.age >= 18** ✓

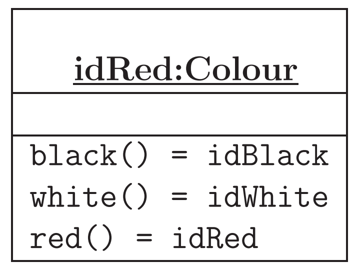
context **Person**
inv: **fleet–>forAll(colour = Colour.black)** ☒

inv: **fleet–>select(colour = Colour.black) –>size() <= 3** ✓

inv: **Car.allInstances –>exists(colour = Colour.red)**

Object Diagrams and OCL Constraints





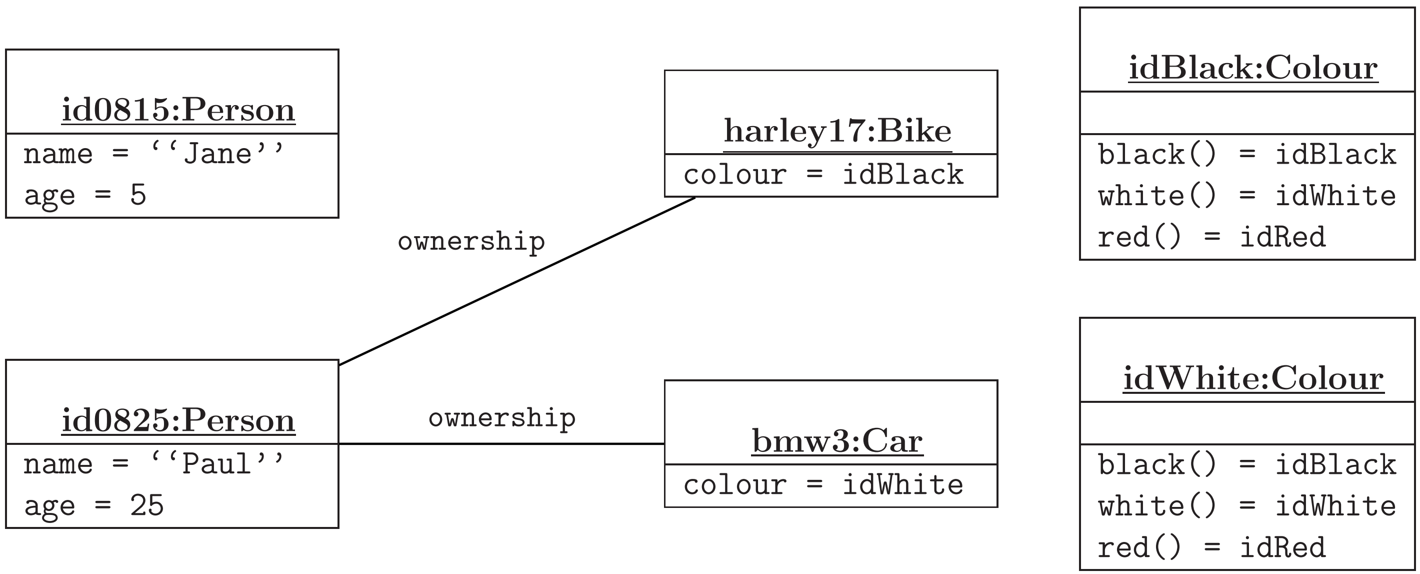
context **Vehicle**
inv: **self.owner.age $>=$ 18** ✓

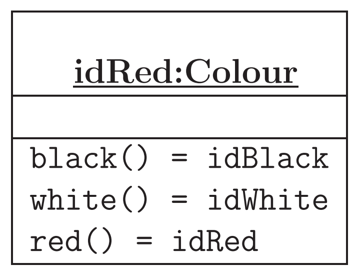
context **Person**
inv: **fleet–$>$forAll(colour = Colour.black)** ☒

inv: **fleet–$>$select(colour = Colour.black) –$>$size() $<$= 3** ✓

inv: **Car.allInstances –$>$exists(colour = Colour.red)** ☒

Object Diagrams and OCL Constraints





context **Person::getName()**
post: **result = name** **?**

context **Person::birthDay()**
pre: **age $\geq$ 0**
post: **age = age@pre + 1** **?**

Why (Formal) Specification?

Importance of Requirements Specification

Advantages of formal requirements spec before implementation:

- **No need to decide on algorithm, but sufficient to describe result**
- **Parts of behaviour can be left open (underspecification)**
- **Possibility of code generation, platform/technology independency model-driven development**
- **Formalisation exhibits bugs & missing requirements in early stage**

Two independent formal models (specification, code):

- **Possibility of formal verification**
- **Find more bugs**
- **More trust in resulting system**