Create your own type system in 1 hour

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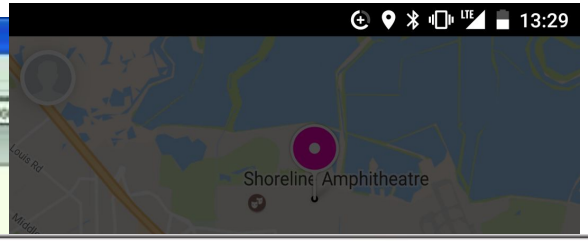
http://CheckerFramework.org/

Motivation



TREND MICRO InterScan™ Web Security Virtual Appliance

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Search

- System Status
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  - − URL Filtering
    - Policies
    - Settings
- Reports
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- Notifications
- + Administration

HTTP Status 500 - java.lang.NullPointerException

type Exception report

message java.lang.NullPointerException

description The server encountered an internal error that prevented it from fulfilling this request.

exception

```
org.apache.jasper.JasperException: java.lang.NullPointerException
        org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:432)
        org.apache.jasper.servlet.JspServlet.serviceJspFile(JspServlet.java:313)
        org.apache.jasper.servlet.JspServlet.service(JspServlet.java:260)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
```

ter.java:73)
77)

java.lang.NullPointerException

```
        org.apache.jsp.urlf_005fsection_005fpolicy_005frule_jsp._jspService(urlf_005fsection_005fpolicy_005frule_jsp.java:742)
        org.apache.jasper.runtime.HttpJspBase.service(HttpJspBase.java:70)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
        org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:388)
        org.apache.jasper.servlet.JspServlet.serviceJspFile(JspServlet.java:313)
        org.apache.jasper.servlet.JspServlet.service(JspServlet.java:260)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
        com.trend.iwss.servlets.filters.CSRFGuardFilter.doFilter(CSRFGuardFilter.java:73)
        com.trend.iwss.servlets.filters.AuthFilter.doFilter(AuthFilter.java:377)
```

java.lang.NullPointerException

Java's type system is too weak

Type checking prevents many errors

```
int i = "hello";
```

Type checking doesn't prevent enough errors

```
System.console().readLine();
```

Java's type system is too weak

Type checking prevents many errors

```
int i = "hello";
```

Type checking doesn't prevent enough errors

NullPointerException

```
System.console().readLine();
```

Prevent null pointer exceptions

Java 8 introduces the `Optional<T>` type

- Wrapper; content may be present or absent
- Constructor: `of(T value)`
- Methods: `boolean isPresent()`, `T get()`

```
Optional<String> maidenName;
```

`Optional` reminds you to check

Without Optional:

possible NullPointerException

```
String mName;
mName.equals(...);

if (mName != null) {
    mName.equals(...);
}
```

With Optional:

possible NoSuchElementException

```
Optional<String> omName;
omName.get().equals(...);

if (omName.isPresent()) {
    omName.get().equals(...);
}
```

possible NullPointerException

Complex rules for using `Optional` correctly!

How not to use Optional

Other guidelines from: Stephen Colebourne, Edwin Dalorzo, Vasco Ferreira C., Brian Goetz, Daniel Olszewski, Nicolai Parlog, Oleg Shelajev, ...

Stuart Marks's rules:

1. Never, ever, use null for an Optional variable or return value.
2. Never use Optional.get() unless you can prove that the Optional is present.
3. Prefer alternative APIs over Optional.isPresent() and Optional.get().
4. It's generally nal for the specific purpose of chaining met
5. If an Optiona chain, or has an intermediate result of Opt ex.
6. Avoid using Optional in fields, method parameters, and collections.
7. Don't use an Optional to wrap any collection type (List, Set, Map). Instead, use an empty collection to represent the absence of values.

Let's enforce the rules with a tool.

Which rules to enforce with a tool

Stuart Marks's rules:

1. **Never**, ever, use null for an Optional variable or return value.
2. **Never** use Optional.get() unless you can prove that the Optional is present.
3. *Prefer* alternative APIs over Optional.isPresent() and Optional.get().
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6. *Avoid* using Optional in fields, method parameters, and collections.
7. **Don't** use an Optional to wrap any collection type (List, Set, Map). Instead, use an empty collection to represent the absence of values.

These are *type system* properties.

Define a type system

$$
\begin{array}{rcll}
\mathtt{h} & \in & \mathtt{Heap} & = \mathtt{Addr} \rightarrow \mathtt{Obj} \\
\iota & \in & \mathtt{Addr} & = \text{Set of Addresses} \cup \{\mathtt{null}_a\} \\
\mathtt{o} & \in & \mathtt{Obj} & = {}^{\mathtt{r}}\mathtt{Type},\ \mathtt{Fields} \\
{}^{\mathtt{r}}\mathtt{T} & \in & {}^{\mathtt{r}}\mathtt{Type} & = \mathtt{OwnerAddr}\ \mathtt{ClassId}\langle\overline{{}^{\mathtt{r}}\mathtt{Type}}\rangle \\
\mathtt{Fs} & \in & \mathtt{Fields} & = \mathtt{FieldId} \rightarrow \mathtt{Addr} \\
\iota & \in & \mathtt{OwnerAddr} & = \mathtt{Addr} \cup \{\mathtt{any}_a\} \\
{}^{\mathtt{r}}\Gamma & \in & {}^{\mathtt{r}}\mathtt{Env} & = \overline{\mathtt{TVarId}\ {}^{\mathtt{r}}\mathtt{Type}};\ \overline{\mathtt{ParId}\ \mathtt{Addr}}
\end{array}
$$

$$
\begin{array}{rcll}
\mathtt{P} & \in & \mathtt{Program} & ::= \overline{\mathtt{Class}},\ \mathtt{ClassId},\ \mathtt{Expr} \\
\mathtt{Cls} & \in & \mathtt{Class} & ::= \mathtt{class}\ \mathtt{ClassId}\langle\overline{\mathtt{TVarI}}\rangle \\
 & & & \mathtt{extends}\ \mathtt{ClassId}\langle\overline{{}^{\mathtt{s}}\mathtt{Ty}}\rangle \\
 & & & \{\ \overline{\mathtt{FieldId}\ {}^{\mathtt{s}}\mathtt{Type}};\ \overline{\mathtt{Met}} \\
{}^{\mathtt{s}}\mathtt{T} & \in & {}^{\mathtt{s}}\mathtt{Type} & ::= {}^{\mathtt{s}}\mathtt{NType} \mid \mathtt{TVarId} \\
{}^{\mathtt{s}}\mathtt{N} & \in & {}^{\mathtt{s}}\mathtt{NType} & ::= \mathtt{OM}\ \mathtt{ClassId}\langle\overline{{}^{\mathtt{s}}\mathtt{Type}}\rangle \\
\mathtt{u} & \in & \mathtt{OM} & ::= \\
\mathtt{mt} & \in & \mathtt{Meth} & ::= \\
 & & \mathtt{MethSig} & ::= \\
\mathtt{w} & \in & \mathtt{Purity} & ::= \\
\mathtt{e} & \in & \mathtt{Expr} & ::= \\
 & & & \mathtt{Expr.MethId}\langle{}^{\mathtt{s}}\mathtt{Type}\rangle(\mathtt{Expr}) \mid \\
 & & & \mathtt{new}\ {}^{\mathtt{s}}\mathtt{Type} \mid ({}^{\mathtt{s}}\mathtt{Type})\ \mathtt{Expr} \\
{}^{\mathtt{s}}\Gamma & \in & {}^{\mathtt{s}}\mathtt{Env} & ::= \overline{\mathtt{TVarId}\ {}^{\mathtt{s}}\mathtt{NType}};\ \overline{\mathtt{ParId}\ {}^{\mathtt{s}}\mathtt{Type}}
\end{array}
$$

$$
\text{OS-Upd}\ \frac{\begin{array}{c}\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}_0, \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \mathtt{h}_0, {}^{\mathtt{r}}\Gamma, \mathtt{e}_2 \rightsquigarrow \mathtt{h}_2, \iota \\ \mathtt{h}' = \mathtt{h}_2[\iota_0.\mathtt{f} := \iota]\end{array}}{\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0.\mathtt{f} = \mathtt{e}_2 \rightsquigarrow \mathtt{h}',}
$$

$$
\text{OS-Read}\ \frac{\begin{array}{c}\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}', \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \iota = \mathtt{h}'(\iota_0)\downarrow_2(\mathtt{f})\end{array}}{\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0.\mathtt{f} \rightsquigarrow \mathtt{h}', \iota}
$$

$$
\text{GT-Read}\ \frac{\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \_\ \langle}{\Gamma \vdash \mathtt{e}_0.\mathtt{f} : \mathtt{N}_0 \rhd fType(\mathtt{C}_0, \mathtt{f})}
$$

$$
\text{GT-Upd}\ \frac{\begin{array}{c}\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \mathtt{u}_0\ \mathtt{C}_0\langle\_\rangle \\ \mathtt{T}_1 = fType(\mathtt{C}_0, \mathtt{f}) \\ \Gamma \vdash \mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1 \\ \mathtt{u}_0 \neq \mathtt{any} \qquad rp(\mathtt{u}_0, \mathtt{T}_1)\end{array}}{\Gamma \vdash \mathtt{e}_0.\mathtt{f} = \mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1}
$$

$$
\text{DYN}\ \frac{\begin{array}{l}\mathtt{h} \vdash {}^{\mathtt{r}}\Gamma : {}^{\mathtt{s}}\Gamma \\ \mathtt{h} \vdash \iota_1 : dyn({}^{\mathtt{s}}\mathtt{N}, \mathtt{h}, {}^{\mathtt{r}}\iota_1) \\ \mathtt{h} \vdash \iota_2 : dyn({}^{\mathtt{s}}\mathtt{T}, \iota_1, \mathtt{h}(\iota_1)\downarrow_1) \\ {}^{\mathtt{s}}\mathtt{N} = \mathtt{u}_N\ \mathtt{C}_N\langle\_\rangle \\ \mathtt{u}_N = \mathtt{this}_u \Rightarrow {}^{\mathtt{r}}\Gamma(\mathtt{this}) \\ free({}^{\mathtt{s}}\mathtt{T}) \subseteq dom(\mathtt{C}_N) \\ \left.\begin{array}{l}{}^{\mathtt{r}}\mathtt{T} = \iota'\ \_\langle\_\rangle \qquad \iota \vdash {}^{\mathtt{r}}\mathtt{T}\ {}^{\mathtt{r}}{<:}\ \iota'\ \mathtt{C}\langle\overline{{}^{\mathtt{r}}\mathtt{T}}\rangle \qquad \iota \vdash {}^{\mathtt{r}}\mathtt{T}\ {}^{\mathtt{r}}{<:}\ \iota'\ \mathtt{C}\langle\overline{{}^{\mathtt{r}}\mathtt{T}_a}\rangle \Rightarrow \iota \vdash \overline{{}^{\mathtt{r}}\mathtt{T}}\ {}^{\mathtt{r}}{<:}\ \overline{{}^{\mathtt{r}}\mathtt{T}_a} \\ \mathrm{dom}(\mathtt{C}) = \overline{\mathtt{X}} \qquad \mathrm{free}({}^{\mathtt{s}}\mathtt{T}) \subseteq \overline{\mathtt{X}} \circ \overline{\mathtt{X}'}\end{array}\right\} \Longrightarrow \mathtt{h} \vdash \iota_2 : dyn({}^{\mathtt{s}}\mathtt{N} \rhd {}^{\mathtt{s}}\mathtt{T}, \mathtt{h}, {}^{\mathtt{r}}\Gamma)\end{array}}{dyn({}^{\mathtt{s}}\mathtt{T}, \iota, {}^{\mathtt{r}}\mathtt{T}, (\overline{\mathtt{X}'\ {}^{\mathtt{r}}\mathtt{T}'}; \_)) = {}^{\mathtt{s}}\mathtt{T}[\iota'/\mathtt{this}, \iota'/\mathtt{peer}, \iota/\mathtt{rep}, \mathtt{any}_a/\mathtt{any}_u, \overline{{}^{\mathtt{r}}\mathtt{T}/\mathtt{X}}, \overline{{}^{\mathtt{r}}\mathtt{T}'/\mathtt{X}'}]}
$$

Define a type system

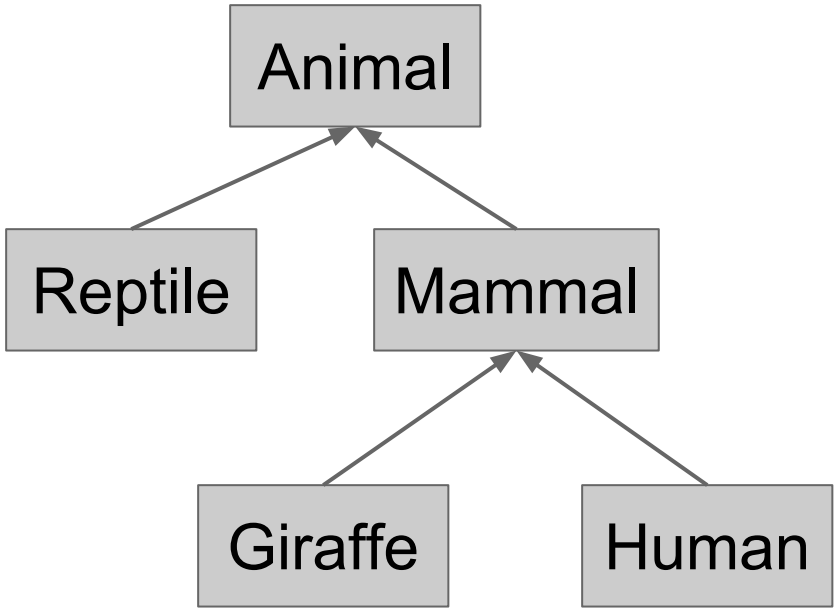
1. **Type hierarchy** (subtyping)
2. **Type rules** (what operations are illegal)
3. **Type introduction** (what types for literals, …)
4. **Dataflow** (run-time tests)

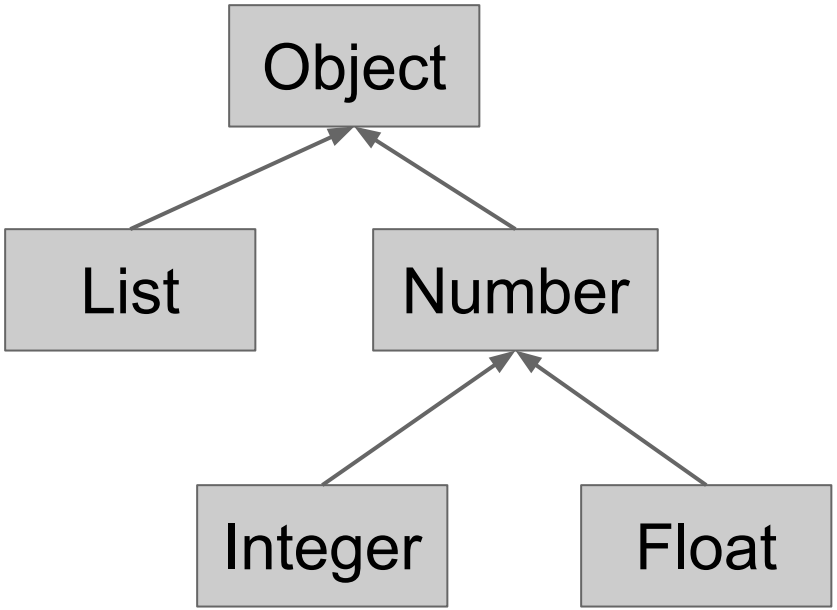
We will define two type systems:
nullness and Optional

Define a type system

1. **Type hierarchy (subtyping)**
2. Type rules (what operations are illegal)
3. Type introduction (what types for literals, …)
4. Dataflow (run-time tests)

1. Type hierarchy

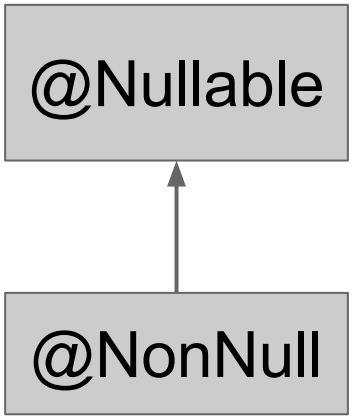




2 pieces of information:

- the types
- their relationships

Type hierarchy for nullness

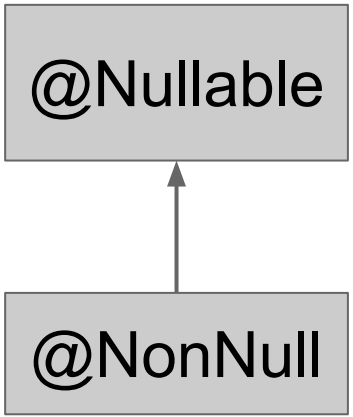


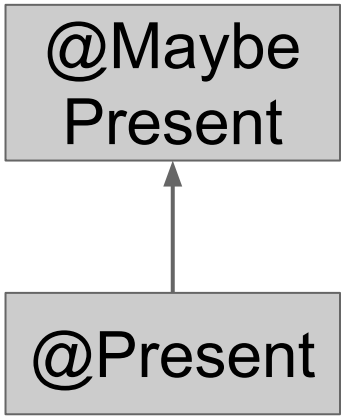
2 pieces of information:

- the types
- their relationships

Type hierarchy for Optional

“Never use Optional.get() unless you can prove that the Optional is present.”



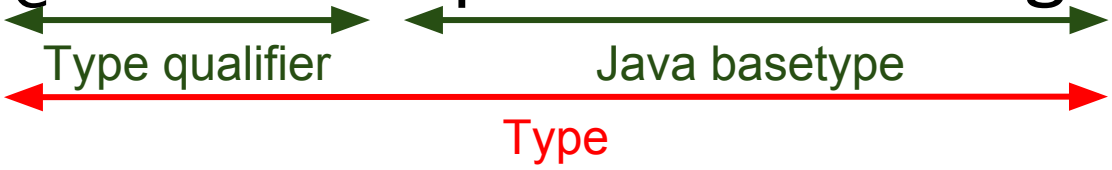


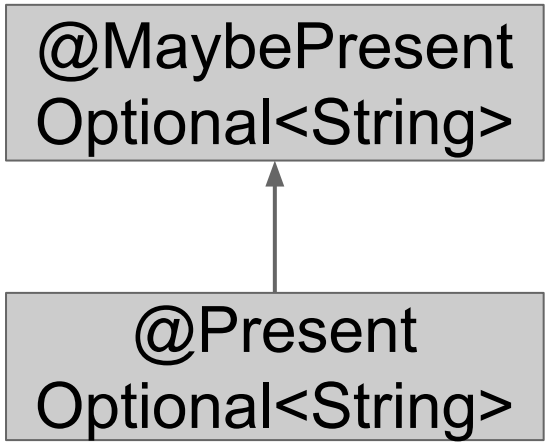
2 pieces of information:

- the types
- their relationships

Type = type qualifier + Java basetype

```
@Present Optional<String> mName;
```





Default qualifier = `@MaybePresent`

so, these types are equivalent:

- `@MaybePresent Optional<String>`
- `Optional<String>`

Define a type system

1. Type hierarchy (subtyping)
2. **Type rules (what operations are illegal)**
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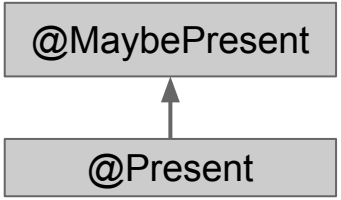
2. Type rules

To prevent null pointer exceptions:

- `expr.field`
  `expr.getValue()`
  receiver must be non-null
- `synchronized (expr) { … }`
  monitor must be non-null
- …

Type rules for Optional



"Never use Optional.get() unless you can prove that the Optional is present."

Only call `Optional.get()` on a receiver of type `@Present Optional`.

```
class Optional<T> {
  T get(Optional<T> this) { ... }
}
```

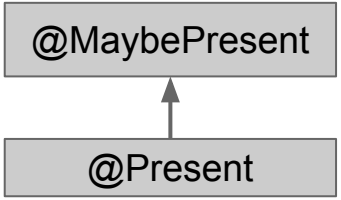
example call:

```
myOptional.get()
```

example call:

```
a.equals(b)
```

Type rules for Optional



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example call:

```
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```
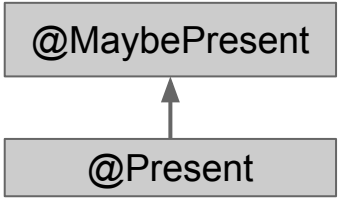

```
class Optional<T> {
  T get(@Present Optional<T> this) {…}
}
```

Type rules for Optional



"Never use Optional.get() unless you can prove that the Optional is present."

Only call `Optional.get()` on a receiver of type `@Present Optional`.

example call:

```
myOptional.get()
```

```
class Optional<T> {
  T get(@Present Optional<T> this) {…}
  T orElseThrow(@Present this, …) {…}
}
```

Define a type system

1. Type hierarchy (subtyping)
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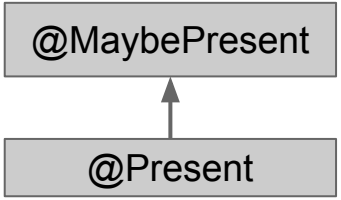
4. Dataflow (run-time tests)

Type introduction rules

For Nullness type system:

- `null : @Nullable`
- `"Hello World" : @NonNull`

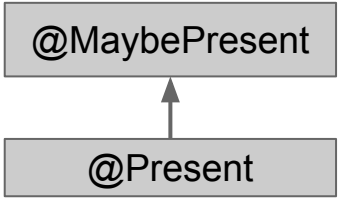
Type introduction for Optional



“Never use Optional.get() unless you can prove that the Optional is present.”

```
Optional<T> of(T value) {...}
Optional<T> ofNullable(T value){...}
```

Type introduction for Optional



“Never use Optional.get() unless you can prove that the Optional is present.”

```
@Present Optional<T> of(T value) {...}
Optional<T> ofNullable(@Nullable T value){...}
```

Define a type system

1. Type hierarchy (subtyping)
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4. **Dataflow (run-time tests)**

Flow-sensitive type refinement

After an operation, give an expression a more specific type

```
@Nullable Object x;
if (x != null) {
  ...
}
...
```

x is @NonNull here

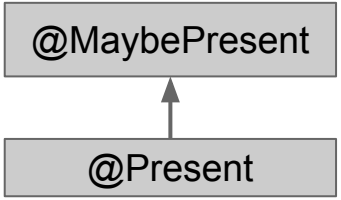
x is @Nullable again

```
@Nullable Object y;
y = new SomeType();
...
y = unknownValue;
...
```

y is @NonNull here

y is @Nullable again

Type refinement for Optional



"Never use Optional.get() unless you can prove that the Optional is present."

After `receiver.isPresent()` returns true, the receiver's type is `@Present`

```
@MaybePresent Optional<String> x;
if (x.isPresent()) {
  …
}
…
```

x is @Present here

x is @MaybePresent again

Now, let's implement it

Follow the instructions in the
Checker Framework Manual

https://checkerframework.org/manual/#creating-a-checker