Exceptions

Syntax

- $\texttt{throw}\ e$

  Jinja: e can be of any class

  Java: e must be of a subclass of `Throwable`

- $\texttt{try}\ e_1\ \texttt{catch}\ (C\ V)\ e_2$

Example:

$\texttt{try}\ \texttt{throw}\ (\texttt{new}\ C)\ \texttt{catch}\ (C\ V)\ \texttt{Var}\ V$
behaves like $\texttt{new}\ C$

System exceptions

System exception classes:

$$\textit{NullPointer}, \textit{ClassCast}, \textit{OutOfMemory} :: \textit{cname}$$

Simplification: System exceptions are allocated *statically* not created *dynamically*:

$$\textit{addr-of-sys-xcpt} :: \textit{cname} \Rightarrow \textit{addr}$$

Abbreviations:

$$\begin{aligned} \texttt{Throw}\ a &\equiv \texttt{throw}(\textit{addr}\ a) \\ \texttt{THROW}\ C &\equiv \texttt{Throw}(\textit{addr-of-sys-xcpt}\ C) \end{aligned}$$

Extension of big step semantics

Variable access

$$\frac{l\ V = \lfloor v \rfloor}{P \vdash \langle \texttt{Var}\ V,(h, l)\rangle \Rightarrow \langle \texttt{Val}\ v,(h, l)\rangle}$$

Uninitialized variables cannot be evaluated

Field access

$$\frac{P \vdash \langle e, s_0 \rangle \Rightarrow \langle addr\ a, (h, l) \rangle \quad h\ a = \lfloor (C, fs) \rfloor \quad fs\ (F, D) = \lfloor v \rfloor}{P \vdash \langle e.F\{D\}, s_0 \rangle \Rightarrow \langle \mathtt{Val}\ v, (h, l) \rangle}$$

Exception creation:

$$\frac{P \vdash \langle e, s_0 \rangle \Rightarrow \langle null, s_1 \rangle}{P \vdash \langle e.F\{D\}, s_0 \rangle \Rightarrow \langle \mathtt{THROW}\ NullPointer, s_1 \rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e, s_0 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_1 \rangle}{P \vdash \langle e.F\{D\}, s_0 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_1 \rangle}$$

Binary operations

$$\frac{P \vdash \langle e_1,s_0\rangle \Rightarrow \langle \texttt{Val}\ v_1,s_1\rangle \quad P \vdash \langle e_2,s_1\rangle \Rightarrow \langle \texttt{Val}\ v_2,s_2\rangle \quad binop\ (bop,\ v_1,\ v_2) = \lfloor v\rfloor}{P \vdash \langle e_1 \text{«}bop\text{»}\ e_2,s_0\rangle \Rightarrow \langle \texttt{Val}\ v,s_2\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e_1,s_0\rangle \Rightarrow \langle \texttt{throw}\ e,s_1\rangle}{P \vdash \langle e_1 \text{«}bop\text{»}\ e_2,s_0\rangle \Rightarrow \langle \texttt{throw}\ e,s_1\rangle}$$

$$\frac{P \vdash \langle e_1,s_0\rangle \Rightarrow \langle \texttt{Val}\ v_1,s_1\rangle \qquad P \vdash \langle e_2,s_1\rangle \Rightarrow \langle \texttt{throw}\ e,s_2\rangle}{P \vdash \langle e_1 \text{«}bop\text{»}\ e_2,s_0\rangle \Rightarrow \langle \texttt{throw}\ e,s_2\rangle}$$

`new`

$$\frac{\begin{array}{c} \textit{new-Addr}\ h = \lfloor a \rfloor \\ P \vdash C\ \textbf{has-fields}\ \textit{FDTs} \\ h' = h(a \mapsto (C,\ \textit{init-fields FDTs})) \end{array}}{P \vdash \langle \texttt{new}\ C,(h,\ l)\rangle \Rightarrow \langle \textit{addr}\ a,(h',\ l)\rangle}$$

Exception creation:

$$\frac{\textit{new-Addr}\ h = \textit{None}}{P \vdash \langle \texttt{new}\ C,(h,\ l)\rangle \Rightarrow \langle \texttt{THROW}\ \textit{OutOfMemory},(h,\ l)\rangle}$$

Cast

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle addr\ a,(h,\ l)\rangle \quad h\ a = \lfloor(D,\ fs)\rfloor \qquad P \vdash D \preceq^* C}{P \vdash \langle \texttt{Cast}\ C\ e,s_0\rangle \Rightarrow \langle addr\ a,(h,\ l)\rangle}$$

Exception creation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle addr\ a,(h,\ l)\rangle \quad h\ a = \lfloor(D,\ fs)\rfloor \qquad \neg\ P \vdash D \preceq^* C}{P \vdash \langle \texttt{Cast}\ C\ e,s_0\rangle \Rightarrow \langle \texttt{THROW}\ ClassCast,(h,\ l)\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}{P \vdash \langle \texttt{Cast}\ C\ e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}$$

Variable assignment

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{Val}\ v,(h,\, l)\rangle \qquad l' = l(V \mapsto v)}{P \vdash \langle V := e,s_0\rangle \Rightarrow \langle \texttt{Val}\ v,(h,\, l')\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}{P \vdash \langle V := e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}$$

Field assignment (1)

$$\frac{\begin{array}{c} P \vdash \langle e_1, s_0 \rangle \Rightarrow \langle addr\ a, s_1 \rangle \qquad P \vdash \langle e_2, s_1 \rangle \Rightarrow \langle \texttt{Val}\ v, (h_2, l_2) \rangle \\ h_2\ a = \lfloor (C, fs) \rfloor \qquad fs' = fs((F, D) \mapsto v) \qquad h_2{}' = h_2(a \mapsto (C, fs')) \end{array}}{P \vdash \langle e_1.F\{D\}\ \texttt{:=}\ e_2, s_0 \rangle \Rightarrow \langle \texttt{Val}\ v, (h_2{}', l_2) \rangle}$$

Exception creation:

$$\frac{P \vdash \langle e_1, s_0 \rangle \Rightarrow \langle null, s_1 \rangle \qquad P \vdash \langle e_2, s_1 \rangle \Rightarrow \langle \texttt{Val}\ v, s_2 \rangle}{P \vdash \langle e_1.F\{D\}\ \texttt{:=}\ e_2, s_0 \rangle \Rightarrow \langle \texttt{THROW}\ NullPointer, s_2 \rangle}$$

Principles:

Evaluate all arguments before throwing an exception.

Propagate exceptions immediately.

Field assignment (2)

Exception propagation:

$$\frac{P \vdash \langle e_1, s_0\rangle \Rightarrow \langle \texttt{throw}\ e', s_1\rangle}{P \vdash \langle e_1.F\{D\}\ \texttt{:=}\ e_2, s_0\rangle \Rightarrow \langle \texttt{throw}\ e', s_1\rangle}$$

$$\frac{P \vdash \langle e_1, s_0\rangle \Rightarrow \langle \texttt{Val}\ v, s_1\rangle \qquad P \vdash \langle e_2, s_1\rangle \Rightarrow \langle \texttt{throw}\ e', s_2\rangle}{P \vdash \langle e_1.F\{D\}\ \texttt{:=}\ e_2, s_0\rangle \Rightarrow \langle \texttt{throw}\ e', s_2\rangle}$$

Method call

Exception creation:

$$\frac{P \vdash \langle e, s_0\rangle \Rightarrow \langle null, s_1\rangle \qquad P \vdash \langle ps, s_1\rangle \; [\Rightarrow] \; \langle map \; \texttt{Val} \; vs, s_2\rangle}{P \vdash \langle e.M(ps), s_0\rangle \Rightarrow \langle \texttt{THROW} \; NullPointer, s_2\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e, s_0\rangle \Rightarrow \langle \texttt{throw} \; e', s_1\rangle}{P \vdash \langle e.M(ps), s_0\rangle \Rightarrow \langle \texttt{throw} \; e', s_1\rangle}$$

$$\frac{\begin{array}{c} P \vdash \langle e, s_0\rangle \Rightarrow \langle \texttt{Val} \; v, s_1\rangle \\ P \vdash \langle es, s_1\rangle \; [\Rightarrow] \; \langle map \; \texttt{Val} \; vs \; @ \; \texttt{throw} \; ex \cdot es', s_2\rangle \end{array}}{P \vdash \langle e.M(es), s_0\rangle \Rightarrow \langle \texttt{throw} \; ex, s_2\rangle}$$

Expression list

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{Val}\ v,s_1\rangle \qquad P \vdash \langle es,s_1\rangle\ [\Rightarrow]\ \langle es',s_2\rangle}{P \vdash \langle e\cdot es,s_0\rangle\ [\Rightarrow]\ \langle \texttt{Val}\ v\cdot es',s_2\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}{P \vdash \langle e\cdot es,s_0\rangle\ [\Rightarrow]\ \langle \texttt{throw}\ e'\cdot es,s_1\rangle}$$

Sequential composition

$$\frac{P \vdash \langle e_0,s_0\rangle \Rightarrow \langle \texttt{Val}\ v,s_1\rangle \qquad P \vdash \langle e_1,s_1\rangle \Rightarrow \langle e_2,s_2\rangle}{P \vdash \langle e_0\texttt{;}\ e_1,s_0\rangle \Rightarrow \langle e_2,s_2\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e_0,s_0\rangle \Rightarrow \langle \texttt{throw}\ e,s_1\rangle}{P \vdash \langle e_0\texttt{;}\ e_1,s_0\rangle \Rightarrow \langle \texttt{throw}\ e,s_1\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}{P \vdash \langle \texttt{if}\ (e)\ e_1\ \texttt{else}\ e_2,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e, s_0 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_1 \rangle}{P \vdash \langle \mathtt{while}\ (e)\ c, s_0 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_1 \rangle}$$

$$\frac{P \vdash \langle e, s_0 \rangle \Rightarrow \langle \mathit{true}, s_1 \rangle \qquad P \vdash \langle c, s_1 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_2 \rangle}{P \vdash \langle \mathtt{while}\ (e)\ c, s_0 \rangle \Rightarrow \langle \mathtt{throw}\ e', s_2 \rangle}$$

`throw`

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle addr\ a,s_1\rangle}{P \vdash \langle \texttt{throw}\ e,s_0\rangle \Rightarrow \langle \texttt{Throw}\ a,s_1\rangle}$$

Exception creation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle null,s_1\rangle}{P \vdash \langle \texttt{throw}\ e,s_0\rangle \Rightarrow \langle \texttt{THROW}\ NullPointer,s_1\rangle}$$

Exception propagation:

$$\frac{P \vdash \langle e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}{P \vdash \langle \texttt{throw}\ e,s_0\rangle \Rightarrow \langle \texttt{throw}\ e',s_1\rangle}$$

`try catch` *(1)*

Normal evaluation:

$$\frac{P \vdash \langle e_1, s_0\rangle \Rightarrow \langle \texttt{Val}\ v_1, s_1\rangle}{P \vdash \langle \texttt{try}\ e_1\ \texttt{catch}\ (C\ V)\ e_2, s_0\rangle \Rightarrow \langle \texttt{Val}\ v_1, s_1\rangle}$$

`try catch` *(2)*

Exception handling:

$$\frac{\begin{array}{c} P \vdash \langle e_1, s_0 \rangle \Rightarrow \langle \texttt{Throw}\ a, (h_1, l_1) \rangle \\ h_1\ a = \lfloor (D, fs) \rfloor \qquad P \vdash D \preceq^* C \\ P \vdash \langle e_2, (h_1, l_1(V \mapsto Addr\ a)) \rangle \Rightarrow \langle e_2', (h_2, l_2) \rangle \end{array}}{P \vdash \langle \texttt{try}\ e_1\ \texttt{catch}\ (C\ V)\ e_2, s_0 \rangle \Rightarrow \langle e_2', (h_2, l_2(V := l_1\ V)) \rangle}$$

Exception propagation:

$$\frac{\begin{array}{c} P \vdash \langle e_1, s_0 \rangle \Rightarrow \langle \texttt{Throw}\ a, (h_1, l_1) \rangle \\ h_1\ a = \lfloor (D, fs) \rfloor \qquad \neg\ P \vdash D \preceq^* C \end{array}}{P \vdash \langle \texttt{try}\ e_1\ \texttt{catch}\ (C\ V)\ e_2, s_0 \rangle \Rightarrow \langle \texttt{Throw}\ a, (h_1, l_1) \rangle}$$

Final expressions redefined (exercise)

$final\ e \equiv (\exists\, v.\ e = \texttt{Val}\ v) \vee (\exists\, a.\ e = \texttt{Throw}\ a)$

$finals\ es \equiv ?$

Lemma If $P \vdash \langle e,s\rangle \Rightarrow \langle e',s'\rangle$ then *final* e'.
If $P \vdash \langle es,s\rangle\ [\Rightarrow]\ \langle es',s'\rangle$ then *finals* es'.

Proof by simultaneous rule induction.

Extension of small step semantics

Variable access

$$\frac{lcl\ s\ V = \lfloor v \rfloor}{P \vdash \langle \texttt{Var}\ V, s\rangle \rightarrow \langle \texttt{Val}\ v, s\rangle}$$

$$lcl\ s\ V = None \Longrightarrow P \vdash \langle Var\ V, s\rangle \rightarrow\ ?$$

Uninitialized variables cannot be reduced

Ill-formed configuration — small step semantics is *stuck*

Field access

Exception creation:

$$P \vdash \langle \mathit{null}.F\{D\},s\rangle \rightarrow \langle \mathtt{THROW}\ \mathit{NullPointer},s\rangle$$

Exception propagation:

$$P \vdash \langle \mathtt{throw}\ e.F\{D\},s\rangle \rightarrow \langle \mathtt{throw}\ e,s\rangle$$

Exception creation:

$$\frac{\textit{new-Addr}\ h = \textit{None}}{P \vdash \langle \texttt{new}\ C,(h,\ l)\rangle \rightarrow \langle \texttt{THROW}\ \textit{OutOfMemory},(h,\ l)\rangle}$$

Cast

Exception creation:

$$\frac{\mathit{hp}\ s\ a = \lfloor(D,\ \mathit{fs})\rfloor \qquad \neg\ P \vdash D \preceq^* C}{P \vdash \langle \texttt{Cast}\ C\ (\mathit{addr}\ a), s\rangle \rightarrow \langle \texttt{THROW}\ \mathit{ClassCast}, s\rangle}$$

Exception propagation:

$$P \vdash \langle \texttt{Cast}\ C\ (\texttt{throw}\ e), s\rangle \rightarrow \langle \texttt{throw}\ e, s\rangle$$

Variable assignment

Exception propagation:

$$P \vdash \langle V \mathrel{:=} \texttt{throw}\ e, s\rangle \to \langle \texttt{throw}\ e, s\rangle$$

Field assignment

Exception creation:

$$P \vdash \langle \mathit{null}.F\{D\} \;\mathtt{:=}\; \mathtt{Val}\; v, s\rangle \rightarrow \langle \mathtt{THROW}\; \mathit{NullPointer}, s\rangle$$

Exception propagation:

$$P \vdash \langle \mathtt{throw}\; e.F\{D\} \;\mathtt{:=}\; e_2, s\rangle \rightarrow \langle \mathtt{throw}\; e, s\rangle$$

$$P \vdash \langle \mathtt{Val}\; v.F\{D\} \;\mathtt{:=}\; \mathtt{throw}\; e, s\rangle \rightarrow \langle \mathtt{throw}\; e, s\rangle$$

Method call

Exception creation:

$$P \vdash \langle \mathit{null}.M(\mathit{map}\ \mathtt{Val}\ \mathit{vs}),s\rangle \rightarrow \langle \mathtt{THROW}\ \mathit{NullPointer},s\rangle$$

Exception propagation:

$$P \vdash \langle \mathtt{throw}\ e.M(\mathit{es}),s\rangle \rightarrow \langle \mathtt{throw}\ e,s\rangle$$

$$P \vdash \langle \mathtt{Val}\ v.M(\mathit{map}\ \mathtt{Val}\ \mathit{vs}\ @\ \mathtt{throw}\ e\cdot \mathit{es}'),s\rangle \rightarrow \langle \mathtt{throw}\ e,s\rangle$$

Expression list

$$\frac{P \vdash \langle e,s\rangle \rightarrow \langle e',s'\rangle}{P \vdash \langle e \cdot es,s\rangle \;[\rightarrow]\; \langle e' \cdot es,s'\rangle}$$

$$\frac{P \vdash \langle es,s\rangle \;[\rightarrow]\; \langle es',s'\rangle}{P \vdash \langle \texttt{Val}\ v \cdot es,s\rangle \;[\rightarrow]\; \langle \texttt{Val}\ v \cdot es',s'\rangle}$$

Sequential composition

$$\frac{P \vdash \langle e,s \rangle \rightarrow \langle e',s' \rangle}{P \vdash \langle e\texttt{;}\ e_2,s \rangle \rightarrow \langle e'\texttt{;}\ e_2,s' \rangle}$$

$$P \vdash \langle \texttt{Val}\ v\texttt{;}\ e_2,s \rangle \rightarrow \langle e_2,s \rangle$$

Exception propagation:

$$P \vdash \langle \texttt{throw}\ e\texttt{;}\ e_2,s \rangle \rightarrow \langle \texttt{throw}\ e,s \rangle$$

Exception propagation:

$$P \vdash \langle \texttt{if}\ (\texttt{throw}\ e)\ e_1\ \texttt{else}\ e_2, s\rangle \rightarrow \langle \texttt{throw}\ e, s\rangle$$

$P \vdash \langle \texttt{while}\,(b)\; c, s\rangle \longrightarrow \langle \texttt{if}\,(b)\,(c\texttt{;}\ \texttt{while}\,(b)\; c)\,\texttt{else}\; unit, s\rangle$

throw

$$\frac{P \vdash \langle e,s \rangle \rightarrow \langle e',s' \rangle}{P \vdash \langle \texttt{throw}\ e,s \rangle \rightarrow \langle \texttt{throw}\ e',s' \rangle}$$

Exception creation:

$$P \vdash \langle \texttt{throw}\ \mathit{null},s \rangle \rightarrow \langle \texttt{THROW}\ \mathit{NullPointer},s \rangle$$

Exception propagation:

$$P \vdash \langle \texttt{throw}\ (\texttt{throw}\ e),s \rangle \rightarrow \langle \texttt{throw}\ e,s \rangle$$

`try catch` *(1)*

$$\frac{P \vdash \langle e,s\rangle \rightarrow \langle e',s'\rangle}{P \vdash \langle \texttt{try}\ e\ \texttt{catch}\ (C\ V)\ e_2,s\rangle \rightarrow \langle \texttt{try}\ e'\ \texttt{catch}\ (C\ V)\ e_2,s'\rangle}$$

Normal evaluation:

$$P \vdash \langle \texttt{try}\ \texttt{Val}\ v\ \texttt{catch}\ (C\ V)\ e_2,s\rangle \rightarrow \langle \texttt{Val}\ v,s\rangle$$

`try catch` *(2)*

Exception handling:

$$[\![hp\ s\ a = \lfloor (D, fs) \rfloor;\ P \vdash D \preceq^* C]\!]$$
$$\Longrightarrow P \vdash \langle \texttt{try Throw}\ a\ \texttt{catch}\ (C\ V)\ e_2, s\rangle \rightarrow$$
$$\langle \{V{:}Class\ C;\ V := addr\ a\texttt{;}\ e_2\}, s\rangle$$

$$[\![hp\ s\ a = \lfloor (D, fs) \rfloor;\ \neg\ P \vdash D \preceq^* C]\!]$$
$$\Longrightarrow P \vdash \langle \texttt{try Throw}\ a\ \texttt{catch}\ (C\ V)\ e_2, s\rangle \rightarrow \langle \texttt{Throw}\ a, s\rangle$$