

0.1 CCC

The section should be a cartesian closed category. That is it should have:

- A Terminal object 1
- Binary products
- Exponentials

0.2 Graded Pre-Monad

The category should have a graded pre-monad. That is:

- An endofunctor indexed by the pre-order on effects: $T : (\mathbb{E}, \leq) \rightarrow \mathbf{Cat}(\mathbb{C}, \mathbb{C})$
- A unit natural transformation: $\eta : \mathbf{Id} \rightarrow T_1$
- A join natural transformation: $\mu_{\epsilon_1, \epsilon_2} : T_{\epsilon_1} T_{\epsilon_2} \rightarrow T_{\epsilon_1 \cdot \epsilon_2}$

Subject to the following commutative diagrams:

0.2.1 Left Unit

$$\begin{array}{ccc} T_\epsilon A & \xrightarrow{T_\epsilon \eta_A} & T_\epsilon T_1 A \\ & \searrow \text{Id}_{T_\epsilon A} & \downarrow \mu_{\epsilon, 1, A} \\ & & T_\epsilon A \end{array}$$

0.2.2 Right Unit

$$\begin{array}{ccc} T_\epsilon A & \xrightarrow{\eta_{T_\epsilon A}} & T_1 T_1 A \\ & \searrow \text{Id}_{T_\epsilon A} & \downarrow \mu_{1, \epsilon, A} \\ & & T_\epsilon A \end{array}$$

0.2.3 Associativity

$$\begin{array}{ccc} T_{\epsilon_1} T_{\epsilon_2} T_{\epsilon_3} A & \xrightarrow{\mu_{\epsilon_1, \epsilon_2, T_{\epsilon_3} A}} & T_{\epsilon_1 \cdot \epsilon_2} T_{\epsilon_3} A \\ \downarrow T_{\epsilon_1} \mu_{\epsilon_2, \epsilon_3, A} & & \downarrow \mu_{\epsilon_1 \cdot \epsilon_2, \epsilon_3, A} \\ T_{\epsilon_1} T_{\epsilon_2 \cdot \epsilon_3} A & \xrightarrow{\mu_{\epsilon_1, \epsilon_2 \cdot \epsilon_3, A}} & T_{\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3} A \end{array}$$

0.3 Tensor Strength

The category should also have tensorial strength over its products and monads. That is, it should have a natural transformation

$$\mathbf{t}_{\epsilon, A, B} : A \times T_\epsilon B \rightarrow T_\epsilon(A \times B)$$

Satisfying the following rules:

0.3.1 Left Naturality

$$\begin{array}{ccc}
A \times T_\epsilon B & \xrightarrow{\text{Id}_A \times T_\epsilon f} & A \times T_\epsilon B' \\
\downarrow \mathfrak{t}_{\epsilon, A, B} & & \downarrow \mathfrak{t}_{\epsilon, A, B'} \\
T_\epsilon(A \times B) & \xrightarrow{T_\epsilon(\text{Id}_A \times f)} & T_\epsilon(A \times B')
\end{array}$$

0.3.2 Right Naturality

$$\begin{array}{ccc}
A \times T_\epsilon B & \xrightarrow{f \times \text{Id}_{T_\epsilon B}} & A' \times T_\epsilon B \\
\downarrow \mathfrak{t}_{\epsilon, A, B} & & \downarrow \mathfrak{t}_{\epsilon, A', B} \\
T_\epsilon(A \times B) & \xrightarrow{T_\epsilon(f \times \text{Id}_B)} & T_\epsilon(A' \times B)
\end{array}$$

0.3.3 Unitor Law

$$\begin{array}{ccc}
1 \times T_\epsilon A & \xrightarrow{\mathfrak{t}_{\epsilon, 1, A}} & T_\epsilon(1 \times A) \\
& \searrow \lambda_{T_\epsilon A} & \downarrow T_\epsilon(\lambda_A) \\
& & T_\epsilon A
\end{array}
\quad \text{Where } \lambda : 1 \times \text{Id} \rightarrow \text{Id} \text{ is the left-unitor. } (\lambda = \pi_2)$$

0.3.4 Commutativity with Join

$$\begin{array}{ccc}
A \times T_{\epsilon_1} T_{\epsilon_2} B & \xrightarrow{\mathfrak{t}_{\epsilon_1, A, T_{\epsilon_2} B}} & T_{\epsilon_1}(A \times T_{\epsilon_2} B) \xrightarrow{T_{\epsilon_1} \mathfrak{t}_{\epsilon_2, A, B}} T_{\epsilon_1} T_{\epsilon_2}(A \times B) \\
& \searrow \text{Id}_A \times \mu_{\epsilon_1, \epsilon_2, B} & \downarrow \mu_{\epsilon_1, \epsilon_2, A \times B} \\
& & A \times T_{\epsilon_1 \cdot \epsilon_2} B \xrightarrow{\mathfrak{t}_{\epsilon_1 \cdot \epsilon_2, A, B}} T_{\epsilon_1 \cdot \epsilon_2}(A \times B)
\end{array}$$

0.4 Subeffecting

For each instance of the pre-order (\mathbb{E}, \leq) , $\epsilon_1 \leq \epsilon_2$, there exists a natural transformation $\llbracket \epsilon_1 \leq \epsilon_2 \rrbracket : T_{\epsilon_1} \rightarrow T_{\epsilon_2}$ that commutes with $\mathfrak{t}_{\epsilon, \cdot}$:

0.4.1 Subeffecting and Tensor Strength

$$\begin{array}{ccc}
A \times T_{\epsilon_1} B & \xrightarrow{\text{Id}_A \times \llbracket \epsilon_1 \leq \epsilon_2 \rrbracket_B} & A \times T_{\epsilon_2} B \\
\downarrow \mathfrak{t}_{\epsilon_1, A, B} & & \downarrow \mathfrak{t}_{\epsilon_2, A, B} \\
T_{\epsilon_1}(A \times B) & \xrightarrow{\llbracket \epsilon_1 \leq \epsilon_2 \rrbracket_{A \times B}} & T_{\epsilon_2}(A \times B)
\end{array}$$

0.5 Subtyping

The denotation of ground types $\llbracket _ \rrbracket_M$ is a functor from the pre-order category of ground types (γ, \leq_γ) to \mathbb{C} . This pre-ordered sub-category of \mathbb{C} is extended with the rule for function subtyping to form a larger pre-ordered sub-category of \mathbb{C} .

$$\text{(Function Subtyping)} \frac{f = \llbracket A' \leq A \rrbracket_M \quad g = \llbracket B \leq B' \rrbracket_M \quad h = \llbracket \epsilon_1 \leq \epsilon_2 \rrbracket}{rhs = \llbracket A \rightarrow \mathbb{M}_{\epsilon_1} B \leq A' \rightarrow \mathbb{M}_{\epsilon_2} B' \rrbracket_M : (T_{\epsilon_1} B)^A \rightarrow (T_{\epsilon_2} B')^{A'}}$$

$$\begin{aligned}
rhs &= (h_{B'} \circ T_{\epsilon_1} g)^A \circ (T_{\epsilon_1} B)^f \\
&= \text{cur}(h_{B'} \circ T_{\epsilon_1} g \circ \text{app}) \circ \text{cur}(\text{app} \circ (\text{Id} \times f))
\end{aligned} \tag{1}$$

0.6 If natural transformation

There exists a natural transformation $\text{If}_A : (\text{Bool} \times (A \times A)) \rightarrow A$ Satisfying the following:

- $\text{If}_A \circ \langle \llbracket \text{true} \rrbracket_M \circ \langle \rangle_\Gamma, \langle t, f \rangle \rangle = t$
- $\text{If}_A \circ \langle \llbracket \text{false} \rrbracket_M \circ \langle \rangle_\Gamma, \langle t, f \rangle \rangle = f$