

## 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 po-monad on effects:  $T : (\mathbb{E}, \cdot, 1, \leq) \rightarrow \mathbf{Cat}(\mathbb{C}, \mathbb{C})$
- 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

$$\begin{array}{ccc}
1 \times T_\epsilon A & \xrightarrow{\mathfrak{t}_{\epsilon, 1, A}} & T_\epsilon(1 \times A) \\
& \searrow \lambda_{T_\epsilon A} & \downarrow T_\epsilon(\lambda_A) \\
& & T_\epsilon A
\end{array}$$

Where  $\lambda : 1 \times \text{Id} \rightarrow \text{Id}$  is the left-unitor. ( $\lambda = \pi_2$ )

**Tensor Strength and Projection** Due to the left-unitor law, we can develop a new law for the commutivity of  $\pi_2$  with  $\mathfrak{t}_\epsilon$ ,

$$\pi_{2, A, B} = \pi_{2, 1, B} \circ (\langle \rangle_A \times \text{Id}_B)$$

And  $\pi_{2, 1}$  is the left unitor, so by tensorial strength:

$$\begin{aligned}
T_\epsilon \pi_2 \circ \mathfrak{t}_{\epsilon, A, B} &= T_\epsilon \pi_{2, 1, B} \circ T_\epsilon (\langle \rangle_A \times \text{Id}_B) \circ \mathfrak{t}_{\epsilon, A, B} \\
&= T_\epsilon \pi_{2, 1, B} \circ \mathfrak{t}_{\epsilon, 1, B} \circ (\langle \rangle_A \times \text{Id}_B) \\
&= \pi_{2, 1, B} \circ (\langle \rangle_A \times \text{Id}_B) \\
&= \pi_2
\end{aligned} \tag{1}$$

So the following commutes:

$$\begin{array}{ccc}
A \times T_\epsilon B & \xrightarrow{\mathfrak{t}_{\epsilon, A, B}} & T_\epsilon(A \times B) \\
& \searrow \pi_2 & \downarrow T_\epsilon \pi_2 \\
& & T_\epsilon B
\end{array}$$

### 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 Commutivity with Unit

$$\begin{array}{ccc}
 A \times B & \xrightarrow{\text{Id}_A \times \eta_B} & A \times T_\epsilon B \\
 & \searrow \eta_{A \times B} & \downarrow \mathfrak{t}_{\epsilon, A, B} \\
 & & T_\epsilon(A \times B)
 \end{array}$$

## 0.5 Commutivity with $\alpha$

Let  $\alpha_{A,B,C} = \langle \pi_1 \circ \pi_1, \langle \pi_2 \circ \pi_1, \pi_2 \rangle \rangle : ((A \times B) \times C) \rightarrow (A \times (B \times C))$

$$\begin{array}{ccc}
 (A \times B) \times T_\epsilon C & \xrightarrow{\mathfrak{t}_{\epsilon, (A \times B), C}} & T_\epsilon((A \times B) \times C) \\
 \downarrow \alpha_{A, B, T_\epsilon C} & & \downarrow T_\epsilon \alpha_{A, B, C} \\
 A \times (B \times T_\epsilon C) & \xrightarrow{\text{Id}_A \times \mathfrak{t}_{\epsilon, B, C}} A \times T_\epsilon(B \times C) \xrightarrow{\mathfrak{t}_{\epsilon, A, (B \times C)}} & T_\epsilon(A \times (B \times C))
 \end{array}$$

**TODO: Needed?**

## 0.6 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  $\mathfrak{t}_{\epsilon, \cdot}$ :

### 0.6.1 Subeffecting and Tensor Strength

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

### 0.6.2 Sub-effecting and Monadic Join

Since the monoid operation on effects is monotone, we can introduce the following diagram.

$$\begin{array}{ccc}
 T_{\epsilon_1} T_{\epsilon_2} & \xrightarrow{T_{\epsilon_1} \llbracket \epsilon_2 \leq \epsilon'_2 \rrbracket_M} & T_{\epsilon_1} T_{\epsilon'_2} \xrightarrow{\llbracket \epsilon_1 \leq \epsilon'_1 \rrbracket_M} \\
 \downarrow \mu_{\epsilon_1, \epsilon_2, \cdot} & & \\
 T_{\epsilon_1 \cdot \epsilon_2} & \xrightarrow{\llbracket \epsilon_1 \cdot \epsilon_2 \leq \epsilon'_1 \epsilon'_2 \rrbracket_M} & 
 \end{array}$$

## 0.7 Subtyping

The denotation of ground types  $\llbracket \cdot \rrbracket_M$  is a functor from the pre-order category of ground types  $(\gamma, \leq_\gamma)$  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  $\mathbb{C}$ .

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

$$\begin{aligned}
 rhs &= (h_{B'} \circ T_{\epsilon_1} g)^{A'} \circ (T_{\epsilon_1} B)^f \\
 &= \text{cur}(h_{B'} \circ T_{\epsilon_1} g \circ \text{app}) \circ \text{cur}(\text{app} \circ (\text{Id}_{T_{\epsilon_1} B^{A'}} \times f))
 \end{aligned}
 \tag{2}$$

## 0.8 If natural transformation

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

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