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# Chapter 1

## Rules for weak Martin-Löf type theory

### 1.1 Dependent type theory

#### 1.1.1 Judgments and contexts

Dependent type theory consists of type judgments, term judgments, and context judgments:

$$A \text{ type} \quad a : A \quad \Gamma \text{ ctx}$$

Rules to form the empty context and to extend the context by a term judgment:

$$\frac{}{() \text{ ctx}} \quad \frac{\Gamma \text{ ctx} \quad \Gamma \vdash A \text{ type}}{(\Gamma, a : A) \text{ ctx}}$$

#### 1.1.2 Variable rule

Variable rule:

$$\frac{\Gamma, a : A, \Delta \text{ ctx}}{\Gamma, a : A, \Delta \vdash a : A}$$

#### 1.1.3 Admissible structural rules

Let  $\mathcal{J}$  be any arbitrary judgment.

Weakening rule:

$$\frac{\Gamma, \Delta \vdash \mathcal{J} \quad \Gamma \vdash A \text{ type}}{\Gamma, a : A, \Delta \vdash \mathcal{J}}$$

Substitution rule:

$$\frac{\Gamma \vdash a : A \quad \Gamma, b : A, \Delta(b) \vdash \mathcal{J}(b)}{\Gamma, \Delta(a) \vdash \mathcal{J}(a)}$$

### 1.2 Basic type formers

The basic type formers of dependent type theory are dependent function types, dependent pair types, and identity types.

### 1.2.1 Formation rules

Formation rules for dependent function types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \prod_{x:A} B(x) \text{ type}}$$

Formation rules for dependent pair types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \sum_{x:A} B(x) \text{ type}}$$

Formation rules for identity types:

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma, a : A, b : A \vdash \text{Id}_A(a, b) \text{ type}}$$

### 1.2.2 Introduction rules

Introduction rules for dependent function types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A \vdash b(x) : B(x)}{\Gamma \vdash \lambda x : A. b(x) : \prod_{x:A} B(x)}$$

Introduction rules for dependent pair types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma, x : A, y : B(x) \vdash \text{pair}_{\sum}^{A,B}(x, y) : \sum_{x:A} B(x)}$$

Introduction rules for identity types:

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma, a : A \vdash \text{refl}_A(a) : \text{Id}_A(a, a)}$$

### 1.2.3 Elimination rules

Elimination rules for dependent function types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma \vdash f : \prod_{x:A} B(x)}{\Gamma, x : A \vdash f(x) : B(x)}$$

Elimination rules for dependent pair types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, z : \sum_{x:A} B(x) \vdash C(z) \text{ type}}{\Gamma \vdash \text{ind}_{\sum}^{A,B,C} : \prod_{g : \prod_{x:A} \prod_{y:B(x)} C(\text{pair}_{\sum}^{A,B}(x, y))} \prod_{z : \sum_{x:A} B(x)} C(z)}$$

Dependent elimination rule for identity types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A, y : A, p : x =_A y \vdash C(x, y, p) \text{ type}}{\Gamma \vdash \text{ind}_{=}^{A,C} : \prod_{t : \prod_{x:A} C(x, x, \text{refl}_A(x))} \prod_{x:A} \prod_{y:A} \prod_{p:x=_A y} C(x, y, p)}$$

### 1.2.4 Computation rules

Computation rules for dependent function types

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A \vdash b(x) : B(x)}{\Gamma \vdash \beta_{\prod_{x:A} B(x)}^{x:A, b(x)} : \prod_{x:A} (\lambda x : A. b(x))(x) =_{B(x)} b(x)}$$

Computation rules for dependent pair types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, z : \sum_{x:A} B(x) \vdash C(z) \text{ type}}{\Gamma \vdash \beta_{\sum}^{A,B,C} : \prod_{g:\prod_{x:A} \prod_{y:B(x)} C(\text{pair}_{\sum}^{A,B}(x,y))} \prod_{x:A} \prod_{y:B(x)} \text{ind}_{\sum}^{A,B,C}(g, \text{pair}_{\sum}^{A,B}(x,y)) =_{C(\text{pair}_{\sum}^{A,B}(x,y))} g(x,y)}$$

Computation rules for identity types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A, y : A, p : x =_A y \vdash C(x, y, p) \text{ type}}{\Gamma \vdash \beta_{\text{ind}=}^{A,C} : \prod_{t:\prod_{x:A} C(x, x, \text{refl}_A(x))} \prod_{x:A} \text{ind}_{\text{Id}}^{A,C}(t, x, x, \text{refl}_A(x)) =_{C(x, x, \text{refl}_A(x))} t(x)}$$

### 1.2.5 Uniqueness rules

Uniqueness rules for dependent function types:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \eta_{\prod_{x:A} B(x)} : \prod_{f:\prod_{x:A} B(x)} f =_{\prod_{x:A} B(x)} \lambda_{\prod_{x:A} B(x)}^{x:A.f(x)}}$$

## 1.3 Judgmental equality

We add to the type theory two additional judgments called judgmental equality of types and judgmental equality of terms:

$$\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma \vdash a \equiv a' : A$$

### 1.3.1 Structural rules for judgmental equality

Reflexivity of judgmental equality

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash A \equiv A \text{ type}} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a : A}{\Gamma \vdash a \equiv a : A}$$

Symmetry of judgmental equality

$$\frac{\Gamma \vdash A \equiv B \text{ type}}{\Gamma \vdash B \equiv A \text{ type}} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A}{\Gamma \vdash b \equiv a : A}$$

Transitivity of judgmental equality

$$\frac{\Gamma \vdash A \equiv B \text{ type} \quad \Gamma \vdash B \equiv C \text{ type}}{\Gamma \vdash A \equiv C \text{ type}} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A \quad b \equiv c : A}{\Gamma \vdash a \equiv c : A}$$

Substitution of judgmentally equal terms:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A \quad \Gamma, x : A, \Delta(x) \vdash B(x) \text{ type}}{\Gamma, \Delta(a) \vdash B(a) \equiv B(b) \text{ type}} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A \quad \Gamma, x : A, \Delta(x) \vdash B(x) \text{ type}}{\Gamma, \Delta(b) \vdash B(a) \equiv B(b) \text{ type}} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A \quad \Gamma, x : A, \Delta(x) \vdash c(x) : B(x)}{\Gamma, \Delta(a) \vdash c(a) \equiv c(b) : B(a)} \\ \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash a \equiv b : A \quad \Gamma, x : A, \Delta(x) \vdash c(x) : B(x)}{\Gamma, \Delta(b) \vdash c(a) \equiv c(b) : B(b)}$$

Judgmental variable conversion rule:

$$\frac{\Gamma \vdash A \equiv B \text{ type} \quad \Gamma, x : A, \Delta \vdash \mathcal{J}}{\Gamma, x : B, \Delta \vdash \mathcal{J}}$$

### 1.3.2 Judgmental congruence rules for dependent function types

$$\begin{array}{c}
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type}}{\Gamma \vdash \prod_{x:A} B(x) \equiv \prod_{x:A'} B'(x) \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A \vdash b(x) : B(x) \quad \Gamma, x : A \vdash b'(x) : B(x) \quad \Gamma, x : A \vdash b(x) \equiv b'(x) : B(x)}{\Gamma \vdash \lambda x : A. b(x) \equiv \lambda x : A. b'(x) : \prod_{x:A} B(x)} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma \vdash f : \prod_{x:A} B(x) \quad f' : \prod_{x:A} B(x) \quad \Gamma \vdash f \equiv f' : \prod_{x:A} B(x)}{\Gamma, x : A \vdash f(x) \equiv f'(x) : B(x)} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A \vdash b(x) : B(x) \quad \Gamma, x : A \vdash b'(x) : B(x) \quad \Gamma, x : A \vdash b(x) \equiv b'(x) : B(x)}{\Gamma \vdash \beta_{\prod_{x:A} B(x)}^{x:A, b(x)} \equiv \beta_{\prod_{x:A} B(x)}^{x:A, b'(x)} : \prod_{x:A} b(x) =_{B(x)} (\lambda x : A. b(x))(x)} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A \vdash B'(x) \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type}}{\Gamma \vdash \eta_{\prod_{x:A} B(x)} \equiv \eta_{\prod_{x:A} B'(x)} : \prod_{f: \prod_{x:A} B(x)} f =_{\prod_{x:A} B(x)} \lambda x : A. f(x)}
\end{array}$$

### 1.3.3 Judgmental congruence rules for dependent pair types

$$\begin{array}{c}
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type}}{\Gamma \vdash \sum_{x:A} B(x) \equiv \sum_{x:A'} B'(x) \text{ type}} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type}}{\Gamma, x : A, y : B(x) \vdash \text{pair}_{\sum}^{A,B} \equiv \text{pair}_{\sum}^{A',B'} : \sum_{x:A} B(x)} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type} \quad \Gamma, z : \sum_{x:A} B(x) \vdash C(z) \equiv C'(z) \text{ type}}{\Gamma \vdash \text{ind}_{\sum}^{A,B,C} \equiv \text{ind}_{\sum}^{A',B',C'} : \prod_{g: \prod_{x:A} \prod_{y: B(x)} C(\text{pair}_{\sum}^{A,B}(x,y))} \prod_{z: \sum_{x:A} B(x)} C(z)} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type} \quad \Gamma, z : \sum_{x:A} B(x) \vdash C(z) \equiv C'(z) \text{ type}}{\Gamma \vdash \beta_{\sum}^{A,B,C} \equiv \beta_{\sum}^{A',B',C'} : \prod_{g: \prod_{x:A} \prod_{y: B(x)} C(\text{pair}_{\sum}^{A,B}(x,y))} \prod_{x:A} \prod_{y: B(x)} \text{ind}_{\sum}^{A,B,C}(g, \text{pair}_{\sum}^{A,B}(x,y)) =_{C(\text{pair}_{\sum}^{A,B}(x,y))} g(x,y)}
\end{array}$$

### 1.3.4 Judgmental congruence rules for identity types

$$\begin{array}{c}
\frac{\Gamma \vdash A \equiv A' \text{ type}}{\Gamma, x : A, y : A \vdash x =_A y \equiv x =_{A'} y} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type}}{\Gamma \vdash \text{refl}_A \equiv \text{refl}_{A'} : \prod_{x:A} x =_A x} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A, y : A, p : x =_A y \vdash C(x, y, p) \equiv C'(x, y, p) \text{ type}}{\Gamma \vdash \text{ind}_{=}^{A,C} \equiv \text{ind}_{=}^{A',C'} : \prod_{t: \prod_{x:A} C(x, x, \text{refl}_A(x))} \prod_{x:A} \prod_{y:A} \prod_{p: x =_A y} C(x, y, p)} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A, y : A, p : x =_A y \vdash C(x, y, p) \equiv C'(x, y, p) \text{ type}}{\Gamma \vdash \beta_{\text{ind}_{=}}^{A,C} \equiv \beta_{\text{ind}_{=}}^{A',C'} : \prod_{t: \prod_{x:A} C(x, x, \text{refl}_A(x))} \prod_{x:A} \text{ind}_{=}^{A,C}(t, x, x, \text{refl}_A(x)) =_{C(x, x, \text{refl}_A(x))} t(x)}
\end{array}$$

## 1.4 Product types

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \times B \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \times B \equiv \sum_{x:A} B \text{ type}}$$

## 1.5 Function types

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \rightarrow B \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \rightarrow B \equiv \prod_{x:A} B \text{ type}}$$

## 1.6 Equivalence types

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \simeq B \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \simeq B \equiv \sum_{f:A \rightarrow B} \left( \sum_{g:B \rightarrow A} \prod_{x:A} g(f(x)) =_A x \right) \times \left( \sum_{h:B \rightarrow A} \prod_{y:B} f(h(y)) =_B y \right) \text{ type}}$$

## 1.7 Function extensionality

Function extensionality rule:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \text{funext}_{A,B} : \prod_{f:\prod_{x:A} B(x)} \prod_{g:\prod_{x:A} B(x)} (f =_{\prod_{x:A} B(x)} g) \simeq \prod_{x:A} f(x) =_{B(x)} g(x)}$$

Judgmental congruence rules for function extensionality:

$$\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type}}{\Gamma \vdash \text{funext}_{A,B} \equiv \text{funext}_{A',B'} : \prod_{f:\prod_{x:A} B(x)} \prod_{g:\prod_{x:A} B(x)} (f =_{\prod_{x:A} B(x)} g) \simeq \prod_{x:A} f(x) =_{B(x)} g(x)}$$

## 1.8 Empty type

Formation rule for the empty type

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \emptyset \text{ type}}$$

Elimination rule for the empty type:

$$\frac{\Gamma, x : \emptyset \vdash C(x) \text{ type}}{\Gamma \vdash \text{ind}_{\emptyset}^C : \prod_{x:\emptyset} C(x) \text{ type}}$$

Judgmental congruence rules for the empty type:

$$\frac{\Gamma, x : \emptyset \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \text{ind}_{\emptyset}^C \equiv \text{ind}_{\emptyset}^{C'} : \prod_{x:\emptyset} C(x) \text{ type}}$$

## 1.9 Unit type

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \mathbb{1} \text{ type}} \quad \frac{\Gamma \text{ ctx}}{\Gamma \vdash \mathbb{1} \equiv \emptyset \rightarrow \emptyset \text{ type}}$$

## 1.10 Type of booleans

Formation rule for the type of booleans

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash 2 \text{ type}}$$

Introduction rule for the type of booleans

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash 0 : 2} \quad \frac{\Gamma \text{ ctx}}{\Gamma \vdash 1 : 2}$$

Elimination rules for the type of booleans:

$$\frac{\Gamma, x : 2 \vdash C(x) \text{ type}}{\Gamma \vdash \text{ind}_2^C : \prod_{a:C(0)} \prod_{b:C(1)} \prod_{x:2} C(x)}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma, x : 2 \vdash \text{typerec}_2^{A,B}(x) \text{ type}}$$

Computation rules for the type of booleans:

$$\frac{\Gamma, x : 2 \vdash C(x) \text{ type}}{\Gamma \vdash \beta_2^{0,C} : \prod_{a:C(0)} \prod_{b:C(1)} \text{ind}_2^C(a, b, 0) =_{C(0)} a}$$

$$\frac{\Gamma, x : 2 \vdash C(x) \text{ type}}{\Gamma \vdash \beta_2^{1,C} : \prod_{a:C(0)} \prod_{b:C(1)} \text{ind}_2^C(a, b, 1) =_{C(1)} b}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash \beta_2^{0,A,B} : \text{typerec}_2^{A,B}(0) \simeq A}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash \beta_2^{1,A,B} : \text{typerec}_2^{A,B}(1) \simeq B}$$

Extensionality rule for the type of booleans:

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{ext}_2 : \prod_{x:2} \prod_{y:2} (x =_2 y) \simeq (\text{typerec}_2^{\emptyset, \mathbb{1}}(x) \simeq \text{typerec}_2^{\emptyset, \mathbb{1}}(y))}$$

Judgmental congruence rules for the type of booleans:

$$\frac{\Gamma, x : 2 \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \text{ind}_2^C \equiv \text{ind}_2^{C'} : \prod_{a:C(0)} \prod_{b:C(1)} \prod_{x:2} C(x)}$$

$$\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma \vdash B \equiv B' \text{ type}}{\Gamma, x : 2 \vdash \text{typerec}_2^{A,B}(x) \equiv \text{typerec}_2^{A',B'}(x) \text{ type}}$$

$$\frac{\Gamma, x : 2 \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \beta_2^{0,C} \equiv \beta_2^{0,C'} : \prod_{a:C(0)} \prod_{b:C(1)} \text{ind}_2^C(a, b, 0) =_{C(0)} a}$$

$$\frac{\Gamma, x : 2 \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \beta_2^{1,C} \equiv \beta_2^{1,C'} : \prod_{a:C(0)} \prod_{b:C(1)} \text{ind}_2^C(a, b, 1) =_{C(1)} b}$$

$$\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma \vdash B \equiv B' \text{ type}}{\Gamma \vdash \beta_2^{0,A,B} \equiv \beta_2^{0,A',B'} : \text{typerec}_2^{A,B}(0) \simeq A}$$

$$\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma \vdash B \equiv B' \text{ type}}{\Gamma \vdash \beta_2^{1,A,B} \equiv \beta_2^{1,A',B'} : \text{typerec}_2^{A,B}(1) \simeq B}$$



## 1.11 Sum types

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A + B \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A + B \equiv \sum_{x:2} \text{typerec}_2^{A,B}(x) \text{ type}}$$

## 1.12 Type of propositions

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isProp}(A) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isProp}(A) \equiv \prod_{x:A} \prod_{y:A} x =_A y \text{ type}}$$

Formation rules for the type of propositions:

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{Prop} \text{ type}}$$

Introduction rule for the type of propositions:

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash \text{proptrunc}_A : \text{isProp}(A)}{\Gamma \vdash A : \text{Prop}}$$

Elimination rules for the type of propositions:

$$\frac{\Gamma \vdash A : \text{Prop}}{\Gamma \vdash A \text{ type}} \quad \frac{\Gamma \vdash A \equiv A' : \text{Prop}}{\Gamma \vdash A \equiv A' \text{ type}}$$

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{proptrunc} : \prod_{A:\text{Prop}} \text{isProp}(A)}$$

Extensionality rules for the type of propositions:

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{ext}_{\text{Prop}} : \prod_{A:\text{Prop}} \prod_{B:\text{Prop}} (A =_{\text{Prop}} B) \simeq (A \simeq B)}$$

## 1.13 Predicate logic

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash [A] \text{ type}} \quad \frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash [A] \equiv \prod_{P:\text{Prop}} (A \rightarrow P) \rightarrow P \text{ type}}$$

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \perp \text{ type}} \quad \frac{\Gamma \text{ ctx}}{\Gamma \vdash \perp \equiv [\emptyset] \text{ type}}$$

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \top \text{ type}} \quad \frac{\Gamma \text{ ctx}}{\Gamma \vdash \top \equiv [\mathbb{1}] \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \neg A \text{ type}} \quad \frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \neg A \equiv [A \rightarrow \emptyset] \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \vee B \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \vee B \equiv [A + B] \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \wedge B \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \wedge B \equiv [A \times B] \text{ type}}$$

$$\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \Rightarrow B \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \Rightarrow B \equiv [A \rightarrow B] \text{ type}}$$

$$\begin{array}{c}
\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \iff B \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash B \text{ type}}{\Gamma \vdash A \iff B \equiv [A \simeq B] \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \exists x : A.B(x) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \exists x : A.B(x) \equiv [\sum_{x:A} B(x)] \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \forall x : A.B(x) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \forall x : A.B(x) \equiv [\prod_{x:A} B(x)] \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isContr}(A) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isContr}(A) \equiv \sum_{x:A} \prod_{y:A} x =_A y \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \exists! x : A.B(x) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \exists! x : A.B(x) \equiv \text{isContr}(\sum_{x:A} B(x)) \text{ type}}
\end{array}$$

## 1.14 Quotient sets

$$\begin{array}{c}
\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{EquivRel}(A) \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{EquivRel}(A) \equiv \sum_{R:A \times A \rightarrow \text{Prop}} \prod_{x:A} R(x, x) \times \prod_{y:A} (R(x, y) \rightarrow R(y, x)) \times \prod_{z:A} (R(x, y) \times R(y, z)) \rightarrow R(x, z) \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash R : \text{EquivRel}(A)}{\Gamma \vdash A/R \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma \vdash R : \text{EquivRel}(A)}{\Gamma \vdash A/R \equiv \sum_{P:A \rightarrow \text{Prop}} \exists x : A. \forall y : A. P(x) =_{\text{Prop}} \pi_1(R)(x, y) \text{ type}}
\end{array}$$

## 1.15 Excluded middle and axiom of choice

$$\begin{array}{c}
\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{lem} : \prod_{P:\text{Prop}} P + \neg P} \\
\\
\frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isSet}(A) \text{ type}} \quad \frac{\Gamma \vdash A \text{ type}}{\Gamma \vdash \text{isSet}(A) \equiv \prod_{x:A} \prod_{y:A} \text{isProp}(x =_A y) \text{ type}} \\
\\
\frac{\Gamma \vdash A \text{ type} \quad \Gamma, x : A \vdash B(x) \text{ type} \quad \Gamma, x : A, y : B(x) \vdash C(x, y) \text{ type}}{\Gamma \vdash \text{choice}_{A,B,C} : (\text{isSet}(A) \times \prod_{x:A} \text{isSet}(B(x))) \rightarrow \forall x : A. \exists y : B(x). C(x, y) \rightarrow \exists g : \prod_{x:A} B(x). \forall x : A. C(x, g(x))} \\
\\
\frac{\Gamma \vdash A \equiv A' \text{ type} \quad \Gamma, x : A \vdash B(x) \equiv B'(x) \text{ type} \quad \Gamma, x : A, y : B(x) \vdash C(x, y) \equiv C'(x, y) \text{ type}}{\Gamma \vdash \text{choice}_{A,B,C} \equiv \text{choice}_{A',B',C'} : \frac{(\text{isSet}(A) \times \prod_{x:A} \text{isSet}(B(x))) \rightarrow \forall x : A. \exists y : B(x). C(x, y) \rightarrow \exists g : \prod_{x:A} B(x). \forall x : A. C(x, g(x))}}
\end{array}$$

## 1.16 Natural numbers type

Formation rules for the natural numbers type:

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \mathbb{N} \text{ type}}$$

Introduction rules for the natural numbers type:

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash 0 : \mathbb{N}} \quad \frac{\Gamma \text{ ctx}}{\Gamma \vdash s : \mathbb{N} \rightarrow \mathbb{N}}$$

Elimination rules for the natural numbers type:

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \text{ type}}{\Gamma \vdash \text{ind}_{\mathbb{N}}^C : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \prod_{x : \mathbb{N}} C(x)}$$

Computation rules for the natural numbers type:

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \text{ type}}{\Gamma \vdash \beta_{\mathbb{N}}^{0,C} : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \text{ind}_{\mathbb{N}}^C(c_0, c_s, 0) =_{C(0)} c_0}$$

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \text{ type}}{\Gamma \vdash \beta_{\mathbb{N}}^{s,C} : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \prod_{x : \mathbb{N}} \text{ind}_{\mathbb{N}}^C(c_0, c_s, s(x)) =_{C(s(x))} c_s(x) (\text{ind}_{\mathbb{N}}^C(c_0, c_s, x))}$$

Judgmental congruence rules for the natural numbers type:

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \text{ind}_{\mathbb{N}}^C \equiv \text{ind}_{\mathbb{N}}^{C'} : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \prod_{x : \mathbb{N}} C(x)}$$

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \beta_{\mathbb{N}}^{0,C} \equiv \beta_{\mathbb{N}}^{0,C'} : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \text{ind}_{\mathbb{N}}^C(c_0, c_s, 0) =_{C(0)} c_0}$$

$$\frac{\Gamma, x : \mathbb{N} \vdash C(x) \equiv C'(x) \text{ type}}{\Gamma \vdash \beta_{\mathbb{N}}^{s,C} \equiv \beta_{\mathbb{N}}^{s,C'} : \prod_{c_0 : C(0)} \prod_{c_s : \prod_{x : \mathbb{N}} C(x) \rightarrow C(s(x))} \prod_{x : \mathbb{N}} \text{ind}_{\mathbb{N}}^C(c_0, c_s, s(x)) =_{C(s(x))} c_s(x) (\text{ind}_{\mathbb{N}}^C(c_0, c_s, x))}$$