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Estimate tools

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Chapter 1

Introduction

Introduction goes here.

Chapter 2

Orders of magnitude

The hyperreals ${}^*\mathbb{R}$ are already defined in Mathlib, using a Lean-canonically chosen ultrafilter on $\mathbb{N}$. One could consider generalizing the hyperreal construction to other filters or ultrafilters, but given the extensive library support for the Mathlib hyperreals, and the fact that it already enjoys enough of a transfer principle for most applications, we will base our theory here on the Mathlib hyperreals.

Definition 1 (Positive hyperreals)**.** PositiveHyperreal, PositiveHyperreal.lesssim, PositiveHyperreal.llThe positive hyperreals ${}^*\mathbb{R}^+$ are the set of hyperreals $X \in {}^*\mathbb{R}$ such that $X > 0$. (Note that X could be infinitesimal or infinite).

If X, Y are positive hyperreals, we write $X \lesssim Y$ if $X \leq CY$ for some real $C > 0$. We write $X \asymp Y$ if $X \lesssim Y \lesssim X$. We write $X \ll Y$ if $X \leq \varepsilon Y$ for all real $\varepsilon > 0$.

Lemma 2 (Lesssim order)**.** *pos-hyperrealPositiveHyperreal.asym$_p$reorder$\lesssim$ is a pre-order on ${}^*\mathbb{R}^+$, with $\asymp$ the associated equivalence relation, and $\ll$ the associated strict order. Any two positive hyperreals are comparable under $\lesssim$.*

Proof. Easy. □

Definition 3 (Orders of magnitude)**.** lesssim-orderOrderOfMagnitude,PositiveHyperreal.order,PositiveHyperre
of the positive hyperreals by the relation of asymptotic equivalence. For a positive hyperreal X, we let $\Theta(X)$ denote the order of magnitude of X; this is a surjection from ${}^*\mathbb{R}^+$ to $\mathcal{O}$.

Lemma 4 (Theta kernel)**.** *ord-defPositiveHyperreal.order$_eq_iff, PositiveHyperreal.order_le_iff, PositiveHyper$
$\Theta(Y)$ if and only if $X \asymp Y$. Similarly, we have $\Theta(X) < \Theta(Y)$ if and only if $X \ll Y$, and $\Theta(X) \leq \Theta(Y)$ if and only if $X \lesssim Y$.*

Proof. Easy. □

Definition 5 (Ordering on magnitudes)**.** theta-kernelOrderOfMagnitude.linearOrderWe linearly order $\mathcal{O}$ by the requirement that $\Theta(X) \leq \Theta(Y)$ if and only if $X \lesssim Y$, and $\Theta(X) < \Theta(Y)$ if and only if $X \ll Y$.

Definition 6 (One)**.** ord-defWe define $1 := \Theta(1)$.

Lemma 7 (Constants trivial)**.** *one-defReal.order*$_o f_p osWehave \Theta(C) = 1$ *for all real* $C > 0$.

Proof. Easy. □

Definition 8 (Arithmetic on magnitudes)**.** theta-kernelOrderOfMagnitude.add, OrderOfMagnitude.mul, OrderOfMagnitude.powWe define addition on $\mathcal{O}$ by the requirement that $\Theta(X) + \Theta(Y) = \Theta(X + Y)$ for positive hyperreals X, Y. Similarly we define multiplication, inverse, and division. We define real exponentiation by requiring that $\Theta(X^\alpha) = \Theta(X)^\alpha$ for positive hyperreals X and real α.

Lemma 9 (Addition is tropical)**.** *mag-arithOrderOfMagnitude.add*$_e q_m ax For all orders of magnitude \Theta(X), \Theta(Y$ *we have* $\Theta(X) + \Theta(Y) = \max(\Theta(X), \Theta(Y))$.

Proof. Easy. □

Corollary 10 (Additive commutative monoid)**.** *tropical-addOrderOfMagnitude.addCommSemigroup, OrderOfMagnitude.add*$_s elf O is an ordered additive idempotent commutative monoid.$

Proof. Easy. □

Lemma 11 (Commutative semiring)**.** *mag-arithOrderOfMagnitude.distrib, OrderOfMagnitude.comm*$_g roup, Or$

Proof. tropical-addEasy. □

Lemma 12 (Power laws)**.** *mag-arithpower*$_i, power'_i, power_i i, power_i v, power_v, power_v i, power_v ii, power_v ii', pou$ *be orders of magnitude, and* α, β *be real numbers.*

(i) *We have* $\Theta(XY)^\alpha = \Theta(X^\alpha Y^\alpha)$ *and* $\Theta(X/Y)^\alpha = \Theta(X^\alpha/Y^\alpha)$.

(ii) *We have* $\Theta(X^{\alpha\beta}) = \Theta(X^\alpha)^\beta$.

(iii) *We have* $\Theta(X)^0 = 1$, $\Theta(X)^1 = \Theta(X)$, *and* $\Theta(X)^{-1} = 1/\Theta(X)$.

(iv) *We have* $\Theta(1)^\alpha = 1$.

(v) *We have* $\Theta(X + Y)^\alpha = \Theta(X)^\alpha + \Theta(Y)^\alpha$ *for* $\alpha \geq 0$.

(vi) *If* $\alpha \geq 0$ *and* $\Theta(X) \leq \Theta(Y)$, *then* $\Theta(X)^\alpha \leq \Theta(Y)^\alpha$.

(vii) *If* $\alpha > 0$, *then* $\Theta(X) \leq \Theta(Y)$, *if and only if* $\Theta(X)^\alpha \leq \Theta(Y)^\alpha$, *and* $\Theta(X) < \Theta(Y)$ *if and only if* $\Theta(X)^\alpha < \Theta(Y)^\alpha$.

(viii) *If* $\alpha \leq 0$ *and* $\Theta(X) \leq \Theta(Y)$, *then* $\Theta(X)^\alpha \geq \Theta(Y)^\alpha$.

(ix) *If* $\alpha < 0$, *then* $\Theta(X) \leq \Theta(Y)$, *if and only if* $\Theta(X)^\alpha \geq \Theta(Y)^\alpha$, *and* $\Theta(X) < \Theta(Y)$ *if and only if* $\Theta(X)^\alpha > \Theta(Y)^\alpha$.

Proof. Straightforward. □

Definition 13 (Log-order of magnitude)**.** mag-arithLogOrderOfMagnitude, OrderOfMagnitude.log, LogOrderOfMagnitude.exp, OrderOfMagnitude.log$_ordered, LogOrderOfMagnitude.exp$
to be the collection of formal logarithms of magnitude $\log(\Theta(X))$ of orders of magnitude $\Theta(X)$. 1, multiplication, and exponentiation of orders of magnitude become 0, addition, and scalar multiplication; and order is preserved. By definition, $\log\colon \mathcal{O} \to \log \mathcal{O}$ is a order isomorphism.

Lemma 14 (Log of addition)**.** *log-order-defOrderOfMagnitude.log*$_addForordersofmagnitude\Theta(X), \Theta(Y),$ *we have* $\log(\Theta(X) + \Theta(Y)) = \max(\log(\Theta(X)), \log(\Theta(Y)))$.

Proof. tropical-addImmediate from Lemma **??**. □

Lemma 15 (Logarithm of multiplication and exponentiation)**.** *OrderOfMagnitude.log*$_mul, OrderOfMagnitude$
we have $\log(1) = 0$ *(and more generally* $\log(C) = 0$ *for any real* $C > 0$*),* $\log(\Theta(X)\Theta(Y)) = \log(\Theta(X)) + \log(\Theta(Y))$*, and* $\log(\Theta(X)/\Theta(Y)) = \log(\Theta(X)) - \log(\Theta(Y))$*. For any real* α*, we have* $\log(\Theta(X)^\alpha) = \alpha \log(\Theta(X))$.

Proof. mag-arith, power-lawStraightforward from Lemma **??** and Lemma **??**. □

Lemma 16 (Ordered vector space)**.** *log-order-defLogOrderOfMagnitude.vec, LogOrderOfMagnitude.posSMulStrictMono*$\log \mathcal{O}$ *is a linearly ordered real vector space.*

Proof. log-multStraightforward from Lemma **??**. □

Lemma 17 (Countable saturation)**.** *saturationLet* $I_1 \supset I_2 \supset \dots$ *be a sequence of internal sets in the hyperreals. If each of the* I_n *is non-empty, then* $\bigcap_{n=1}^\infty I_n$ *is non-empty.*

Proof. Write each I_n as an ultraproduct of $I_{n,m}$. Then, we can find a nested sequence $E_1 \supset E_2 \supset \dots$ of large sets in the ultrafilter such that $\bigcap_{n \le n_0} I_{n,m}$ is non-empty for all $m \in E_{n_0}$ and all n_0, and also $n_0 \notin E_{n_0}$. If we then pick x_m to lie in $\bigcap_{n \le n_0} E_{n,m}$ where n_0 is the largest number for which $m \in E_{n_0}$, the ultralimit of the x_m will have the required properties. □

Lemma 18 (Completeness)**.** *Let* $I_1 \supset I_2 \supset \dots$ *be a decreasing sequence of non-empty open intervals (possibly unbounded) in* $\mathcal{O}$*. Then* $\bigcap_{n=1}^\infty I_n$ *is non-empty.*

Proof. saturation Pull back each of the I_n to the hyperreals as a countable intersection of internal sets, and apply Lemma **??**. □

Lemma 19 (Completeness, II)**.** *Let* $I_1 \supset I_2 \supset \dots$ *be a decreasing sequence of non-empty intervals (possibly unbounded or closed) in* $\mathcal{O}$*. Then* $\bigcap_{n=1}^\infty I_n$ *is non-empty.*

Proof. completeness If one of the I_n is a singleton, the claim is straightforward. Otherwise, replace each I_n by its interior and use Lemma **??**. □