Lior Silberman's Math 322 Problem Set 1, due 14/9/2017

Practice and supplementary problems, and any problems specifically marked "OPT" (optional), "SUPP" (supplemenetary) or "PRAC" (practice) are *not for submission*. It is possible that the grader will not mark all problems.

Practice problems

The following problem is a review of the axioms for a vector space.

P1 Let X be a set. Carefully show that pointwise addition and scalar multiplication endow the set $\mathbb{R}^X$ of functions from X to $\mathbb{R}$ with the structure of an $\mathbb{R}$-vectorspace. Meditate on the case $X = [n] = \{0, 1, \ldots, n-1\}$.

P2 (Euclid's Lemma) Let a, b, q, r be four integers with $b = aq + r$. Show that the pairs $\{a, b\}$ and $\{a, r\}$ have the same sets of common divisors, hence the same greatest common divisor.

P3. Consider the equation $7x + 11y = 1$ for unknowns $x, y \in \mathbb{Z}$.
(a) Exhibit infinitely many solutions.
(*b) Show that you found *all* the solutions.

The integers

1. Show that for any integer k, one of the integers $k, k+2, k+4$ is divisible by 3.

2. (Modular arithmetic; see notes for the notation or wait for Tuesday lecture)
(a) Give a simple rule for the remainder obtained when dividing 3^n by 13, for $n \in \mathbb{Z}_{\geq 0}$.
PRAC Check that $2^{12} \equiv 1\,(13)$.
(b) Let k be the smallest positive integer such that $2^k \equiv 1\,(13)$. Show that $k|12$.
PRAC Check that $2^6 \equiv -1\,(13)$, $2^4 \equiv 3\,(13)$.
(c) Use the last check to show that $k = 12$.
(d) Show that $2^i \equiv 2^j\,(13)$ iff $i \equiv j\,(12)$.

3. Let a, n be positive integers and let $d = \gcd(a, n)$. Show that the equation $ax \equiv 1\,(n)$ has a solution iff $d = 1$.

4. Let $f \colon \mathbb{Z} \to \mathbb{Z}$ be *additive*, in that for all $x, y \in \mathbb{Z}$ we have $f(x+y) = f(x) + f(y)$.
PRAC Check that for any $a \in \mathbb{Z}$, $f_a(x) = ax$ is additive.
(a) Show that $f(0) = 0$ (hint: $0 + 0 = 0$).
(b) Show that $f(-x) = -f(x)$ for all $x \in \mathbb{Z}$.
(c) Show by induction on n that for all $n \geq 1$, $f(n) = f(1) \cdot n$.
(d) Show that every additive map is of the form f_a for some $a \in \mathbb{Z}$.
RMK Let H be the set of additive maps $\mathbb{Z} \to \mathbb{Z}$. We showed that the function $\varphi \colon H \to \mathbb{Z}$ given by $\varphi(f) = f(1)$ is a bijection (with inverse $\psi(a) = f_a$).
SUPP Show that the bijections φ, ψ are themselves additive maps (addition in H is defined pointwise).

(hints on reverse)

(for 2(a): try the first few values to find the pattern, then use induction)
(for 2(b): divide 12 by k using the theorem on division with remainder)
(for 2(c): consider in turn each proper divisor of 12)
(for 2(d): as in part b replace i,j with their remainders mod 12. Then, assuming $i > j$, consider $2^{i+(12-j)}$)

Supplementary problems I: Functions

The following problem will be used in the upcoming discussion of permutations.

A. Let X,Y,Z,W be sets and let $f\colon X \to Y$, $g\colon Y \to Z$ and $h\colon Z \to W$ be functions. Recall that the *composition* $g \circ f$ is the function $g \circ f\colon X \to Z$ such that $(g \circ f)(x) = g(f(x))$ for all $x \in X$.
   (a) Show that composition is *associative*: that $h \circ (g \circ f) = (h \circ g) \circ f$ (recall that functions are equal if they have the same value at every x).
   (b) f is called *injective* or *one-to-one* (1:1) if $x \neq x'$ implies $f(x) \neq f(x')$. Show that if $g \circ f$ is injective then so is f.
   (c) g is called *surjective* or *onto* if for every $z \in Z$ there is $y \in Y$ such that $g(y) = z$. Show that if $g \circ f$ is surjective then so is g.
   (d) Suppose that f,g are both surjective or both injective. In either case show that the same holds for $g \circ f$.
   (e) Give an example of a set X and $f,g\colon X \to X$ such that $f \circ g \neq g \circ f$.

Supplementary Problems II: Subsemigroups of $(\mathbb{Z}_{\geq 0}, +)$

B. The Kingdom of Ruritania mints coins in the denominations $d_1, \ldots, d_r$ Marks (d_i are positive integers, of course). Let $d = \gcd(d_1, \ldots, d_r)$.
   (a) Show that every payable sum (total value of a combination of coins) is a multiple of d Marks.
   (b) Show that there exists $N \geq 1$ such that any multiple of d Marks exceeding N can be expressed using the given coins.
   (c) Let $H \subset \mathbb{Z}_{\geq 0}$ be the set of sums that can be paid using the coins. Show that H is closed under addition.

   DEF H is called the *subsemigroup of* $\mathbb{Z}_{\geq 0}$ *generated* by $\{d_1, \ldots, d_r\}$.

C. (partial classification of subsemigroups of $\mathbb{Z}_{\geq 0}$) Let $H \subset \mathbb{Z}_{\geq 0}$ be closed under addition.
   (a) Show that either $H = \{0\}$or there are $N,d \geq 1$ such that d divides every element of h, and such that H contains all multiples of d exceeding N.
   Hint: Enumerate the elements of H in increasing order as $\{h_i\}_{i=1}^{\infty}$ and consider the sequence $\{\gcd(h_1, \ldots, h_m)\}_{m=1}^{\infty}$.
   (b) Conclude that H is *finitely generated*: there are $\{d_1, \ldots, d_r\} \subset H$ such that H is obtained as in problem C.

Supplementary Problems III: Additive groups in $\mathbb{R}$.

D. (just linear algebra)

(a) Show that the usual addition and multiplication by rational numbers endow $\mathbb{R}$ with the structure of a vector space over the field $\mathbb{Q}$.

(b) Let $f\colon \mathbb{R} \to \mathbb{R}$ be additive ($f(x+y) = f(x) + f(y)$). Show that f is $\mathbb{Z}$-linear: that $f(nx) = nf(x)$ for all $x \in \mathbb{R}, n \in \mathbb{Z}$.

(c) Show that f is $\mathbb{Q}$-linear: $f(rx) = rf(x)$ for all $r \in \mathbb{Q}$.

(d) Let $B \subset \mathbb{R}$ be a basis for $\mathbb{R}$ as a $\mathbb{Q}$-vector space (this is called a *Hamel basis*). Use B to construct a $\mathbb{Q}$-linear map $\mathbb{R} \to \mathbb{R}$ which is not of the form $x \mapsto ax$.

E. (add topology ...) Let $f\colon \mathbb{R} \to \mathbb{R}$ be additive.

(a) Suppose that f is *continuous*. Show that $f(x) = ax$ where $a = f(1)$.

(b) (If you have taken Math 420) Suppose that f is *Lebesgue* (*or Borel*) *measurable*. Show that there is $a \in \mathbb{R}$such that $f(x) = ax$ a.e.

(c) ("$\mathbb{R}$ has no field automorphisms") Let $f\colon \mathbb{R} \to \mathbb{R}$ satisfy $f(x+y) = f(x) + f(y)$ and $f(xy) = f(x)f(y)$. Show that either $f(x) = 0$ for all x or $f(x) = x$ for all x.