Appendix A
Useful Mathematical Concepts and Notation

For a set S we write card S for the cardinality of S. In other words, card S denotes the number of elements of S. The number n is the set of all numbers i (including 0) such that $i < n$. Thus, $3 = \{0, 1, 2\}$. (The interested reader may check that therefore $0 = \varnothing$, $1 = \{0\} = \{\varnothing\}$, $2 = \{\varnothing, \{\varnothing\}\}$ and $3 = \{\varnothing, \{\varnothing\}, \{\varnothing, \{\varnothing\}\}\}$.) Thus, $i < n$ and $i \in n$ are synonymous. Writing $f : k \to n$ means that f is a function defined on all numbers $< k$, with values $< n$.

We shall write $\langle x_0, x_1, \cdots, x_{n-1}\rangle$ for the tuple of length n consisting in x_0, x_1, etc., in that order. We make no commitment about the real nature of tuples; you may think of them as functions from the set n to the domain. (In that case they are the same as strings.) The length of $\vec{x} := \langle x_0, \cdots, x_{n-1}\rangle$ is denoted by $|\vec{x}|$. We write x_0 in place of $\langle x_0\rangle$ even though they are technically distinct. Tuple formation is not associative. So, $\langle x_0, \langle x_1, x_2\rangle\rangle$ is not the same as $\langle\langle x_0, x_1\rangle, x_2\rangle$. If $\vec{x} = \langle x_0, \cdots, x_{m-1}\rangle$ and $\vec{y} = \langle y_0, \cdots, y_{n-1}\rangle$ are tuples, the concatenation is denoted as follows.

$$\vec{x} \cdot \vec{y} := \langle x_0, \cdots, x_{m-1}, y_0, \cdots, y_{n-1}\rangle \tag{A.1}$$

Repetitions are not eliminated, so this is a sequence of length $m + n$.

Given two sets, A and B, $A \times B$ is the set of pairs $\langle a, b\rangle$ such that $a \in A$ and $b \in B$. Given an indexed family A_i, $i \in I$, of sets, $\mathsf{X}_{i \in I} A_i$ is the set of functions from I to the union of the A_i such that $f(i) \in A_i$ for all $i \in I$. (Thus, technically, $A_0 \times A_2$ is *not* the same as $\mathsf{X}_{i \in 2} A_i$, though the difference hardly matters.) Let A and B be sets. A **relation from** A **to** B is a subset of $A \times B$. We write $x \; R \; y$ in place of $\langle x, y\rangle \in R$. A **partial function from** A **to** B is a relation from A to B such that $x \; R \; y$ and $x \; R \; z$ implies $y = z$. A **function from** A **to** B is a partial function from A to B where for every $x \in A$ there is a $y \in B$ such that $x \; R \; y$. We write $f : A \to B$ to say that f is a function from A to B and $f : A \hookrightarrow B$ to say that f is a partial function from A to B. If $f : A \to B$ and $g : B \to C$ then $g \circ f : A \to C$ is defined by $(g \circ f)(x) := g(f(x))$. We write dom$(f)$ for the set of all $a \in A$ such that f is defined on a. If $f : A^n \hookrightarrow B$ and $S \subseteq A$ then we write $f \restriction S$ for the following function

$$(f \restriction S)(\vec{x}) := \begin{cases} f(\vec{x}) & \text{if } \vec{x} \in S^n \text{ and } f(\vec{x}) \text{ is defined,} \\ \text{undefined} & \text{else.} \end{cases} \tag{A.2}$$

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A somewhat simpler definition is

$$f \restriction S := f \cap (S^n \times A). \tag{A.3}$$

If $X \subseteq A$ is a set we write $f[X] := \{f(a) : a \in X, a \in \mathrm{dom}(f)\}$. This is the **direct image of** X **under** f. In particular, $\mathrm{rng}(f) := f[A]$ is the **range** of f. f is **surjective** or **onto** if $\mathrm{rng}(f) = B$. f is **injective** or **into** if for all x, y: if $f(x)$ and $f(y)$ are defined then either $x = y$ or $f(x) \neq f(y)$. A **permutation** is a surjective function $f : n \to n$. It is easily seen that if f is surjective it is also injective. There are $n! := n(n-1)(n-2)\cdots 2 \cdot 1$ permutations of an n element set ($n > 0$).

When $f : A \times B \to C$ is a function, we say that it is **independent** of its first argument if for all $x, x' \in A$ and $y \in B$, $f(x, y) = f(x', y)$. (If $A \neq B$ we also say that f is independent of A rather than of its first argument.) Pick $x \in A$ and define $\hat{f} : B \to C$ by $\hat{f}(y) := f(x, y)$. If f is independent of its first argument, $\hat{f}$ is independent of the choice of x. For partial functions there are some subtleties. We say that f is **weakly independent of** A if for all $x, x' \in A$ and $y \in B$, if $f(x, y)$ and $f(x', y)$ exist, they are equal. f is **strongly independent of** A if for all $x, x' \in A$ and $y \in B$, if $f(x, y)$ exists then so does $f(x', y)$ and they are equal. By default, for a partial function independence of A means weak independence. Independence of its second argument (or of B) is defined similarly. Similarly, if f has several arguments, it may be weakly of strongly independent of any of them.

If $f : A \to C$ and $g : A \to D$ are functions, then $f \times g : x \mapsto \langle f(x), g(y)\rangle$ is a function from A to $C \times D$. Every function from A to $C \times D$ can be decomposed into two functions, in the following way. Let $\pi_C : \langle x, y\rangle \mapsto x$ and $\pi_2 : \langle x, y\rangle \mapsto y$ be the projections from $C \times D$ to C and D, respectively. Then we have the general equation

$$f = (\pi_c \circ f) \times (\pi_D \circ f). \tag{A.4}$$

and so the functions $\pi_C \circ f$ and $\pi_D \circ f$ are the decomposition. This picture changes when we turn to partial functions. From a pair $f : A \hookrightarrow C$ and $g : A \hookrightarrow D$ we can form the partial function

$$(f \times g)(x) := \begin{cases} \langle f(x), g(x)\rangle & \text{if both } f(x) \text{ and } g(x) \text{ are defined,} \\ \text{undefined} & \text{else.} \end{cases} \tag{A.5}$$

Unfortunately, $f \times g$ does not allow to recover f and g uniquely. The problem is this: we have

$$\mathrm{dom}(f \times g) = \mathrm{dom}(f) \cap \mathrm{dom}(g). \tag{A.6}$$

However, from an intersection it is not easy to recover the individual sets. If $A = \{0\}$, $f = \{\langle 0, c\rangle\}$ and $g = \varnothing$ (the empty partial function) then $f \times g = \varnothing$. However, also $\varnothing \times \varnothing = \varnothing$.

Given a number n, a bijective function $f : n \to n$ is called a **permutation of** n. Π_n denotes the set of all permutations of n. Permutations are most conveniently described using the following notation. Pick a number $i < n$. The **cycle** of i is the largest sequence of the form $i, f(i), f(f(i)), \cdots$ in which no member is repeated. The set $\{i, f(i), f^2(i), \cdots\}$ is also called the **orbit** of i under f. We write this cycle in the form $(i f(i) f(f(i)) \cdots f^{k-1}(i))$. An example is (2567), which says that f maps 2 to 5, 5 to 6, 6 to 7 and 7 to 2. The **order of the cycle** is its length, k. So, the order is the smallest number k for which $f^k(i) = i$. For if $f^k(i) = f^m(i)$ for some $m < k$ then also $f^{k+1}(i) = f^{m+1}(i)$ (since f is a function), and $f^{k-1}(i) = f^{m-1}(i)$ (since f is bijective, so its inverse is a function, too). It follows that $f^{k-m}(i) = i$ and since $m < k$, we must have $m = 0$. (Else we have found a number $j > 0$ smaller than k such that $f^j(i) = i$.) Cycles can be cyclically rotated: for example, $(2567) = (5672)$. It is easy to see that any two distinct orbits are disjoint. A permutation thus partitions the set n into orbits, and defines a unique cycle on each of the orbits. In writing down permutations, cycles of length 1 are omitted. Cycles permute and can be cyclically rotated. Thus we write (2567)(3)(1)(04) and (2567)(04), (5672)(40)(3), (04)(2567) interchangeably. The permutation that changes nothing is also denoted by ().

A **group** is a structure $\mathscr{G} = \langle G, 1, ^{-1}, \cdot \rangle$, where $1 \in G$, $^{-1} : G \to G$ and $\cdot : G \times G \to G$ are such that for all $x, y, z \in G$:

1. $1 \cdot x = x \cdot 1 = x$.
2. $x^{-1} \cdot x = x \cdot x^{-1} = 1$.
3. $x \cdot (y \cdot z) = (x \cdot y) \cdot z$.

We say that x^{-1} is the **inverse** of x and that $x \cdot y$ (also written xy) is the **product** of x and y. The set Π_n forms a group. The product is defined by $(f \cdot g)(x) := f(g(x))$. The unit is the permutation (). The inverse is obtained as follows. The inverse of a cycle $(i_0 i_1 \cdots i_{k-1})$ is the cycle $(i_{k-1} i_{k-2} \cdots i_1 i_0)$. The inverse of a series of disjoint cycles is obtained by inverting every cycle individually. (Note that if c and d are disjoint cycles, then $c \cdot d = d \cdot c$.) A **subgroup** of $\mathscr{G}$ is a triple $\mathscr{H} = \langle H, 1^*, ^{-1^*}, \cdot^* \rangle$ where $H \subseteq G$, $1^* = 1$, $x^{-1*} = x^{-1}$ and $x \cdot^* y = x \cdot y$. It is stated without proof that if $\mathscr{H}$ is a subgroup of $\mathscr{G}$ then $|H|$ divides $|G|$.

A **signature** is a pair $\langle F, \Omega \rangle$ (often written simply Ω) where F is a set (the set of **function symbols**) and $\Omega : F \to \mathbb{N}$ a function, assigning each function symbol an arity. An **Ω-algebra** is a pair $\mathfrak{A} = \langle A, I \rangle$ such that for every $f \in F$, $I(f) : A^{\Omega(f)} \to A$. We also write $f^{\mathfrak{A}}$ for $I(f)$. A **partial Ω-algebra** is a pair $\mathfrak{A} = \langle A, I \rangle$ where for each $f \in F$, $I(f) : A^{\Omega(f)} \hookrightarrow A$. A **weak congruence** on $\mathfrak{A}$ is an equivalence relation $\Theta \subseteq A^2$ such that the following holds.

> If $a_i \,\Theta\, b_i$ for every $i < \Omega(f)$ and both $I(f)(a_0, \cdots, a_{\Omega(f)-1})$ and $I(f)(b_0, \cdots, b_{\Omega(f)-1})$ exist then they are equal.

Θ is **strong** if whenever $a_i \;\Theta\; b_i$ for all $i < \Omega(f)$ then $I(f)(a_0, \cdots, a_{\Omega(f)-1})$ exists iff $I(f)(b_0, \cdots, b_{\Omega(f)-1})$ exists as well. If Θ is a strong congruence we can construct the so-called **quotient algebra** $\mathfrak{A}/\Theta$.

$$\begin{aligned} a/\Theta &:= \{b : a\ \Theta\ b\} \\ A/\Theta &:= \{a/\Theta : a \in A\} \\ (I/\Theta)(f)(a_0/\Theta, \cdots, a_{\Omega(f)-1}/\Theta) &:= (f(a_0, \cdots, a_{\Omega(f)-1}))/\Theta \\ \mathfrak{A}/\Theta &:= \langle A/\Theta, I/\Theta\rangle \end{aligned} \tag{A.7}$$

It is to be observed that $(I/\Theta)(f)$ is well defined; the value of the function does not depend on the choice of representatives. Moreover, whether or not it is defined is also independent of the choice of representatives, since the congruence is strong.

A homomorphism between partial algebras $\mathfrak{A} = \langle A, I\rangle$ and $\mathfrak{B} = \langle B, J\rangle$ is a function $h : A \to B$ such that for all $f \in F$ and all $a_0, \cdots, a_{\Omega(f)-1} \in A$:

$$h(I(f)(a_0, \cdots, a_{\Omega(f)-1})) = J(f)(h(a_0), \cdots, h(a_{\Omega(f)-1})). \tag{A.8}$$

If $\mathfrak{A} = \langle A, I\rangle$ and $\mathfrak{C} = \langle C, J\rangle$ are partial algebras then the **product** of $\mathfrak{A}$ and $\mathfrak{C}$ is defined by

$$(I \times J)(f)(\langle a_0, c_0\rangle, \cdots, \langle a_{\Omega(f)-1}, c_{\Omega(f)-1}\rangle) := \langle I(f)(\vec{a}), J(f)(\vec{c})\rangle. \tag{A.9}$$

We write $\mathfrak{A} \times \mathfrak{C}$ for the product.

In the domain of algebra, the term functions and polynomial functions are very important. Their definition is notoriously difficult since one is often required to use variables where this creates problems due to choices of alphabetical variants. Instead, I offer the following definition, which only uses functions and compositions.

① All projections $p_i^n : A^n \to A$ defined by $p_i^n(a_0, \cdots, a_{n-1}) := a_i$ are term functions.

② If $g_i : A^{m_i} \to A$, $i < \Omega(f)$, are term functions and $p := \sum_{i<\Omega(f)} m_i$, then $f \circ \langle g_0, \cdots, g_{\Omega(f)-1}\rangle : A^p \to A$ is a term function where

$$f \circ \langle g_0, \cdots, g_{\Omega(f)-1}\rangle(\vec{c}_0, \cdots, \vec{c}_{\Omega(f)-1}) := f(g_0(\vec{c}_0), \cdots, g_{\Omega(f)-1}(\vec{c}_{\Omega(f)-1}))$$

is a term function.

③ If $g : A^n \to A$ is a term function and $i < j$ then $g \circ \Delta_{ij}^n : A^{n-1} \to A$ defined by $\left(g \circ \Delta_{ij}^n\right)(a_0, \cdots, a_{n-2}) := g(a_0, \cdots, a_{j-1}, a_i, a_j, a_{j+1}, \cdots, a_{n-1})$ also is a term function.

(For a partial algebra, replace "function" everywhere by "partial function".) Term functions are often described by means of terms such as $(x + y) \cdot z$ but this is inaccurate. A **polynomial** is defined to a term function over the expanded algebra $\mathfrak{A}^A$, where for each $a \in A$ we have added a constant $\underline{a}$ to the language, whose interpretation is fixed to A. (Alternatively, it is the closure under ①–③ of the set of functions containing $A^0 \to A : \varnothing \to a$ for each a.)

Symbols

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