Math 55a: Honors Advanced Calculus and Linear Algebra

The Fundamental Theorem of Algebra

A little field algebra. Let $F$ be any field, and $P$ a polynomial in one variable $T$ with
coefficients in $F$ (the ring of such polynomials is usually denoted by $F[T]$). For any
t_1 \in F$, polynomial division yields a polynomial $P_1 \in F[T]$ and scalar $c \in F$ such that
$P(T) = (T - t_1)P_1(t) + c$; moreover, substituting $t_1$ for $T$, we find that the “remainder"
c is just $P(t_1)$. In particular, $P(t_1) = 0$ if and only if $P(T) = (T - t_1)P_1(t)$ for some
polynomial $P_1$. Recall that a solution of the polynomial equation $P(t) = 0$ is called a
root of $P$; so we are saying that $t_1$ is a root of $P$ if and only if $P(T) = (T - t_1)P_1(t)$
for some polynomial $P_1$.

Assume now that $P$ is not identically zero [i.e., not the zero element of $F[T]$]. We say
that $P$ factors completely if there exist $a, t_1, \ldots, t_n \in F$ such that

$$P(T) = a \prod_{j=1}^{n} (T - t_j).$$

Necessarily $a \neq 0$ and $n = \deg P$. Then $P(t) = 0$ if and only if $t = t_j$ for some $j$; i.e.,
the roots of $P$ are the $t_j$. This gives us the implication (i)⇒(ii) in our next result:

Proposition. The following conditions on a field $F$ are equivalent:

i) Every nonzero polynomial in $F[t]$ factors completely.

ii) Every nonconstant polynomial in $F[t]$ has a root in $F$.

Proof: It remains to prove (ii)⇒(i). We do this by induction on the degree $n$ of our
polynomial. The case $n = 0$ is trivial: then our polynomial is a constant, and we may
let $a$ be that constant. Suppose then that we have done the case of degree $n = d$, and
let $P$ be a polynomial of degree $d + 1$. Since $d + 1 > 0$, this polynomial is nonconstant,
so by (ii) it has a root $t_1$. But then $P(T) = (T - t_1)P_1(t)$ for some polynomial $P_1$ of
degree $d$. By the inductive hypothesis, $P_1$ factors completely; thus so does $P$. □

A field is said to be algebraically closed if satisfies the two equivalent conditions of this
proposition.

The case $F = \mathbb{C}$. The Fundamental theorem of algebra is the statement that the field
$\mathbb{C}$ of complex numbers is algebraically closed. That is, every nonconstant $P \in \mathbb{C}[T]$ has
a complex root. We prove this by contradiction. Suppose, then, that $P$ is a nonconstant
polynomial with no complex roots; thus $P$ maps $\mathbb{C}$ to $\mathbb{C}^*$. Write $P(T) = \sum_{k=0}^n a_k T^k$
with $a_n$ nonzero; we may also assume $a_0$ nonzero (why?). The idea of the proof is to
look at how many times $P(t)$ winds around the origin as $t$ moves around the circle of
radius $r$. For small $r$, we expect that $P(t)$ moves in a small neighborhood of $a_0$, so
the winding number is zero; for large $r$, we expect that $P(t)$ is dominated by $a_k t^k$,
which winds around the origin $n$ times. But $n \neq 0$, and the winding number shouldn’t
change as $r$ increases from “small” to “large”.

To make a proof out of this, we need to formalize the notion of “winding number” in
this setting, and study its properties. You will encounter many of these ideas again in
greater generality when you study algebraic topology.

For \( \alpha \in \mathbb{R} \), define \( e(\alpha) = \cos 2\pi \alpha + i\sin 2\pi \alpha \); this is a complex number of absolute
value 1, with \( e(\alpha) = e(\beta) \iff \alpha \equiv \beta \mod \mathbb{Z} \). Every nonzero complex number \( z \)
can be written as \( |z|e(\alpha) \) with \( \alpha \in \mathbb{R} \) uniquely determined mod \( \mathbb{Z} \). [You'll recognize
\((|z|, 2\pi \alpha)\) as the “polar coordinates” of \( z \).] Moreover \( \alpha \) is a continuous function from
\( \mathbb{C}^\ast \) to \( \mathbb{R}/\mathbb{Z} \); thus \( \alpha \circ P : \mathbb{C} \to \mathbb{R}/\mathbb{Z} \) is also continuous. For each \( r > 0 \), the complex
numbers \( t \) with \( |t| = r \) also constitute a circle homeomorphic with \( \mathbb{R}/\mathbb{Z} \). So we are
in effect studying continuous maps from the circle \( \mathbb{R}/\mathbb{Z} \) to itself. We shall attach
to such a map an integral invariant called its “winding number”, and show that it is
locally constant on \( C(\mathbb{R}/\mathbb{Z}, \mathbb{R}/\mathbb{Z}) \). We shall then prove that the winding number of
\( \alpha \mapsto \alpha(P(re(\alpha))) \) is 0 for small \( r \) and \( n \) for large \( r \), which will complete our proof of
the Fundamental Theorem of Algebra.

First let \( f \in C([0,1], \mathbb{R}/\mathbb{Z}) \). We shall prove: there exists \( \tilde{f} : C([0,1], \mathbb{R}) \) such that
\( f(0) = 0 \) and \( f(a) \equiv f(0) + f(0) \mod \mathbb{Z} \) for all \( a \in [0,1] \); one can think of \( \tilde{f}(a) \)
as measuring the net local change of \( f \) from 0 to \( a \). Uniqueness is easy: the difference
between two such functions is a continuous map from \([0,1] \) to \( \mathbb{Z} \), which is thus constant;
since the functions agree at \( a = 0 \), they must agree throughout. For existence, use
compactness of \([0,1] \) to find \( \delta > 0 \) such that \( |a-b| \leq \delta \) implies \( |f(a) - f(b)| < 1/4 \), and
inductively construct \( f \) on \([0, n\delta] \) for \( n = 1, 2, 3, \ldots, \lfloor \delta^{-1} \rfloor \), and finally on all of \([0,1] \).
(This sketch will be filled in in class.)

So we have a function \( \tilde{f} \) from \( C([0,1], \mathbb{R}/\mathbb{Z}) \) to \( C([0,1], \mathbb{R}) \). We next claim that
this function is continuous. Indeed if for some \( d(f,g) < \epsilon \) for some \( \epsilon < 1/2 \) then
d(\( \tilde{f}, \tilde{g} \)) < 2\epsilon. This is because \( (\tilde{f} - \tilde{g}) \in C([0,1], \mathbb{R}) \) vanishes at 0 and only takes on
values within \( \epsilon \) of an integer, so cannot escape from \( N_{\epsilon}(0) \).

Now, a continuous function from \( \mathbb{R}/\mathbb{Z} \) to \( \mathbb{R}/\mathbb{Z} \) is just a function \( f \in C([0,1], \mathbb{R}/\mathbb{Z}) \)
such that \( f(0) = f(1) \). For such a function, \( f(1) \in \mathbb{Z} \). This integer \( f(1) \) is the winding
number (a.k.a. “degree”) of \( f \). For instance, \( f \) is an integer \( n \) the map \( a \mapsto f(a) \)
\( (\text{winding?}) \) has winding number \( n \). From our analysis thus far it follows that
\( f/2 \) then \( f,g \) have the same winding numbers. Thus if \( \phi, \psi : \mathbb{R}/\mathbb{Z} \to \mathbb{C}^\ast \)
\( > |\phi(a) - \psi(a)| \) for all \( a \in \mathbb{R}/\mathbb{Z} \) then \( \alpha \circ \phi \) and \( \alpha \circ \psi \) have the same
umber.

of \( P \) and Heine-Borel in \( \mathbb{C} \) (or a more explicit \( \epsilon, \delta \) computation), the map

\( \ell : \mathbb{R}/\mathbb{Z}, \mathbb{R}/\mathbb{Z} \) taking \( r \) to the function \( \ell(r(\psi(a))) \) is continuous.

order of \( f_r \) is independent of \( r \). But for \( r = 0 \) the function \( f_r \) is
number zero. For \( r > \max(1, \sum_{k=1}^{n-1} |a_k|/|a_n|) \), we have

\( |a_r(r(\psi(a))) - a_n(r(e(a)))^n| < |a_n(r(e(a)))^n| \) \( \iff |a_n|^n \),

nï¿½ihomomorphism as the
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