Title

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All manifolds: connected, oriented, 2nd countable, Hausdorff.

1.1 Compact-Open Topology

- For X, Y topological spaces, consider

$$Y^X = C(X,Y) = \hom_{\text{Top}}(X,Y) \coloneqq \left\{ f: X \to Y \;\middle|\; f \text{ is continuous} \right\}.$$

  - General idea: it's nice to *cartesian closed* categories, which require *exponential objects* or *internal homs*: i.e. for every hom set, there is some object in the category that represents it (i.e. here we'd like the homs to again be spaces).
  - Can make this work if we assume WHCG: weakly Hausdorff and compactly generated.
    * Weakly Hausdorff: every continuous image of a compact Hausdorff space into it is closed.
    * Compactly generated: sets are closed iff their intersection with every compact subspace is closed.
  - Topologize with the *compact-open* topology $\mathcal{O}_{\text{CO}}$:

$$U \in \mathcal{O}_{\text{CO}} \iff \forall f \in U, \quad f(K) \subset Y \text{ is open for every compact } K \subseteq X.$$

    * If $Y = (Y, d)$ is a metric space, this is the topology of "uniform convergence on compact sets": for $f_n \to f$ in this topology iff

$$\|f_n - f\|_{\infty, K} \coloneqq \sup \left\{ d(f_n(x), f(x)) \;\middle|\; x \in K \right\} \overset{n\to\infty}{\to} 0 \quad \forall K \subseteq X \text{ compact}.$$

      In words: $f_n \to f$ uniformly on every compact set.

- If X itself is compact and Y is a metric space, $C(X,Y)$ can be promoted to a metric space with $d(f,g) = \sup_{x \in X}(f(x), g(x))$.
- Useful in analysis: when is a family of functions $\mathcal{F} = \{f_\alpha\} \subset \hom_{\mathrm{Top}}(X,Y)$ compact? Essentially answered by Arzela-Ascoli

Theorem 1.1 *(Ascoli).*
If X is locally compact Hausdorff and (Y,d) is a metric space, a family $\mathcal{F} \subset \hom_{\mathrm{Top}}(X,Y)$ has compact closure $\iff$ $\mathcal{F}$ is equicontinuous and $F_x := \left\{ f(x) \;\middle|\; f \in \mathcal{F} \right\} \subset Y$ has compact closure.

Corollary 1.2 *(Arzela).*
If $\{f_n\} \subset \hom_{\mathrm{Top}}(X,Y)$ is an equicontinuous sequence and $F_x := \{f_n(x)\}$ is bounded for every X, it contains a uniformly convergent subsequence.

- Useful in Number Theory / Rep Theory / Fourier Series: can take G to be a locally compact abelian topological group and define its Pontryagin dual $\widehat{G} := \hom_{\mathrm{TopGrp}}(G, S^1)$ where we consider $S^1 \subset \mathbb{C}$.
  * Can integrate with respect to the Haar measure μ, define L^p spaces, and for $f \in L^p(G)$ define a Fourier transform $\widehat{f} \in L^p(\widehat{G})$.

$$\widehat{f}(\chi) := \int_G f(x)\overline{\chi(x)}d\mu(x).$$

- So define

$$\mathrm{Map}(X,Y) := (\hom_{\mathrm{Top}}(X,Y), \mathcal{O}_{\mathrm{CO}}) \qquad \text{where } \mathcal{O}_{\mathrm{CO}} \text{ is the compact-open topology.}$$

$\mathrm{Map}(X,Y) = \hom_{\mathrm{Top}}(X,Y)$ equipped with the compact-open topology.

- Can immediately consider some interesting spaces via the functor $\mathrm{Map}(\,\cdot\,, Y)$:

$$\begin{aligned} X = \{\mathrm{pt}\} &\rightsquigarrow \quad \mathrm{Map}(\{\mathrm{pt}\}, Y) \cong Y \\ X = I &\rightsquigarrow \quad \mathcal{P}Y := \{f : I \to Y\} = Y^I \\ X = S^1 &\rightsquigarrow \quad \mathcal{L}Y := \left\{ f : S^1 \to Y \right\} = Y^{S^1}. \end{aligned}$$

Note: take basepoints to obtain the base path space PY, the based loop space ΩY.

- Importance in homotopy theory: the path space fibration $\Omega(Y) \hookrightarrow P(Y) \xrightarrow{\gamma \mapsto \gamma(1)} Y$ (plays a role in "homotopy replacement", allows you to assume everything is a fibration and use homotopy long exact sequences).
- Adjoint property: there is a homeomorphism

$$\begin{aligned} \mathrm{Map}(X \times Z, Y) &\leftrightarrow_{\cong} \mathrm{Map}(Z, \mathrm{Map}(X,Y)) \\ H : X \times Z \to Y &\iff \tilde{H} : Z \to \mathrm{Map}(X,Y) \\ (x,z) \mapsto H(x,z) &\iff z \mapsto H(\,\cdot\,, z). \end{aligned}$$

  Categorically, $\hom(X, \cdot\,) \leftrightarrow (X \times \,\cdot\,)$ form an adjoint pair in Top.

A form of this adjunction holds in any cartesian closed category.

- Fun fact: with some mild point-set conditions (Locally compact and Hausdorff),

$$\pi_0 \mathrm{Map}(X,Y) = \{[f], \text{ homotopy classes of maps } f : X \to Y\},$$

  i.e. two maps f,g are homotopic $\iff$ they are connected by a path in $\mathrm{Map}(X,Y)$.

    - Proof:

$$\mathcal{P}\mathrm{Map}(X,Y) = \mathrm{Map}(I, \mathrm{Map}(X,Y)) \cong \mathrm{Map}(Y \times I, X),$$

      and just check that $\gamma(0) = f \iff H(x,0) = f$ and $\gamma(1) = g \iff H(x,1) = g$.
    - Note that we can interpret the RHS as the space of paths
  - Now we can bootstrap up to play fun recursive games by applying the pathspace *endofunctor* $\mathrm{Map}(I, \cdot)$: define

$$\mathrm{Map}_I^1(X,Y) := \mathrm{Map}(I, \mathrm{Map}(X,Y)) = \mathcal{P}\mathrm{Map}(X,Y)$$

  and then

$$\begin{aligned}\mathrm{Map}_I^2(X,Y) &:= \mathrm{Map}(I, \mathrm{Map}_I^1(X,Y)) \\ &\cong \mathrm{Map}(I, \mathrm{Map}(I, \mathrm{Map}(X,Y))) \quad = \mathcal{P}(\mathcal{P}(X,Y)) \\ &\cong \mathrm{Map}(I, \mathrm{Map}(Y \times I, X)) \\ &:= \mathcal{P}\mathrm{Map}(Y \times I, X).\end{aligned}$$

  Interpretation: we can consider paths in the *space* of paths, and paths between homotopies, and homotopies between homotopies, ad infinitum!

  This in fact defines a *monad* on spaces: an endofunctor that behaves like a monoid.

1.2 Isotopy

???

1.3 Self-Homeomorphisms

- In any category, the automorphisms form a group.
  - In a general category $\mathcal{C}$, we can always define the group $\mathrm{Aut}_{\mathcal{C}}(X)$.
    - If the group has a topology, we can consider $\pi_0 \mathrm{Aut}_{\mathcal{C}}(X)$, the set of path components.
    - Since groups have identities, we can consider $\mathrm{Aut}_{\mathcal{C}}^0(X)$, the path component containing the identity.
  - So we make a general definition, the *extended mapping class group*:

$$\mathrm{MCG}_{\mathcal{C}}^{\pm}(X) := \mathrm{Aut}_{\mathcal{C}}(X) / \mathrm{Aut}_{\mathcal{C}}^0(X).$$

  - Here the $\pm$ indicates that we take both orientation preserving and non-preserving automorphisms.
  - Has an index 2 subgroup of orientation-preserving automorphisms, $\mathrm{MCG}^+(X)$.
- Now restrict attention to

$$\mathrm{Homeo}(X) := \mathrm{Aut}_{\mathrm{Top}}(X) = \left\{ f \in \mathrm{Map}(X,X) \;\middle|\; f \text{ is an isomorphism} \right\}$$

equipped with $\mathcal{O}_{\mathrm{CO}}$.

  - Taking $\mathrm{MCG}_{\mathrm{Top}}^{\pm}(X)$ yields ??

- Similarly, we can do all of this in the smooth category:

$$\mathrm{Diffeo}(X) \coloneqq \mathrm{Aut}_{C^\infty}(X).$$

  - Taking $\mathrm{MCG}_{C^\infty}(X)$ yields ??

- Similarly, we can do this for the homotopy category of spaces:

$$\mathrm{ho}(X) \coloneqq \{[f]\}.$$

  - Taking $\mathrm{MCG}(X)$ here yields *homotopy classes of self-homotopy equivalences.*

- For topological manifolds: Isotopy classes of homeomorphisms
  - In the compact-open topology, two maps are isotopic iff they are in the same component of $\pi \mathrm{Aut}(X)$.

- For surfaces: $\mathrm{MCG}(S)$ on the Teichmuller space $T(S)$, yielding a SES

$$0 \to \mathrm{MCG}(S) \to T(S) \to \widetilde{\mathcal{M}}_g(S) \to 0$$

  where the last term is the moduli space of Riemann surfaces homeomorphic to X.

  - $T(S)$ is the moduli space of complex structures on S, up to the action of homeomorphisms that are isotopic to the identity:
    * Points are isomorphism classes of marked Riemann surfaces
  - Used in the Neilsen-Thurston Classification (for a compact orientable surface, a self-homeomorphism is isotopic to one which is any of: periodic: reducible (preserves some simple closed curves), or pseudo-Anosov (has directions of expansion/contraction))

- Generated by Dehn twists: a self homeomorphism
- Any finite group is $\mathrm{MCG}(X)$ for some compact hyperbolic 3-manifold X.

Theorem 1.3 ***(Dehn-Neilsen-Baer).***

$$\mathrm{MCG}^{\pm}(\Sigma_g) \cong \mathrm{Out}(\pi_1(\Sigma_g)).$$

1.4 Dehn Twists

Claim: Let $A \coloneqq \left\{ z \in \mathbb{C} \,\middle|\, 1 \le |z| \le 2 \right\}$, then $\mathrm{MCG}(A) \cong \mathbb{Z}$, generated by the map

$$\begin{aligned} \tau_0 : \mathbb{C} &\to \mathbb{C} \\ z &\mapsto \exp\left(2\pi i |z|\right) z. \end{aligned}$$

See complex function plotter

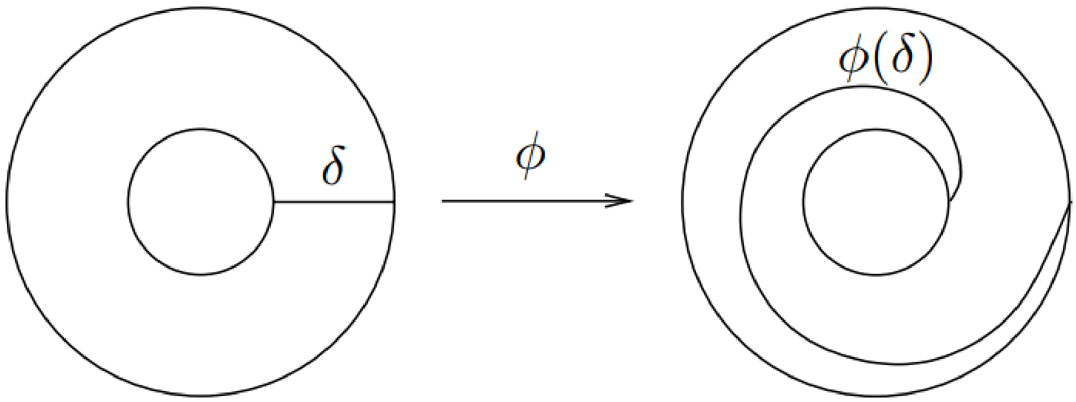

Figure 2.5 A generator for $\mathrm{Mod}(A)$.

Figure 1: Image