Formalizing the Gromov-Hausdorff Space

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Abstract

The Gromov-Hausdorff space is usually defined in textbooks as "the space of all compact metric spaces up to isometry". We describe a formalization of this notion in the Lean proof assistant, insisting on how we need to depart from the usual informal viewpoint of mathematicians on this object to get a rigorous formalization.

The Gromov-Hausdorff space is the space of all nonempty compact metric spaces up to isometry. It has been introduced by Gromov in [Gro81], and plays now an important role in branches of geometry and probability theory. Its intricate nature of a space of equivalence classes of spaces gives rise to interesting formalization questions, both from the point of view of the interface with the rest of the library and on design choices for definitions and proofs. This text is devoted to a discussion of these issues: it describes a formalization of the main features of the Gromov-Hausdorff space in the Lean proof assistant, developed at Microsoft Research by Leonardo de Moura [dMKA+15], within the library `mathlib` [mc20].

This text is written with two audiences in mind: it can be read by curious mathematicians who want to learn the basics of the Gromov-Hausdorff space, and by formalizers who want to learn about the challenges raised by the formalization of an unusual mathematical object such as this one. It should be reasonably self-contained.

In Section 1, we give a purely mathematical description of the Gromov-Hausdorff space and its salient features. In Section 2, we give an overview of our formalization. The last three sections are devoted to specific interesting points that were raised during this formalization. More specifically, Section 3 discusses the possible choices of definition for the Gromov-Hausdorff space. Section 4 explains how preexisting gaps in the `mathlib` library had to be filled to show that the Gromov-Hausdorff distance is realized. Section 5 focuses on a particularly subtle inductive construction involved in the proof of the completeness of the Gromov-Hausdorff space, and the shortcomings of Lean 3 that had to be circumvented to formalize it.

1   A primer on the Gromov-Hausdorff space

In this paragraph, we give a quick overview on the Gromov-Hausdorff space as presented in mathematics textbooks. See for instance [BBI01, Section 7.3] or [Pet16, Section 10.1].

Given two nonempty bounded subsets A and B of a metric space X, there is a way to tell how close these are, as subsets of X, through their *Hausdorff distance* $d_H^X(A, B)$. It is the infimum of those r such that A is included in the r-neighborhood of B (i.e., the set of points within distance at most r of a point in B) and B is included in the r-neighborhood of A. This r is finite as A and B are bounded and nonempty, and zero if and only if A and B have the same closure. In particular, d_H^X induces a distance on the space of nonempty bounded closed subsets of X, and also on the space $\mathcal{K}_X$ of its nonempty compact subsets. This distance is very well behaved: $(\mathcal{K}_X, d_H^X)$ is complete (resp. second-countable, resp. compact) if X is.

Much more recently, Gromov has introduced in [Gro81] a way to compare metric spaces even when they are not embedded in a common space. His motivation was to be able to prove that some classes of Riemannian manifolds were totally bounded or compact, in a suitable sense, to deduce uniformity statements over all manifolds in these classes. While there are many variants of his notion of distance, we will focus in this article on the simplest one, over nonempty compact metric spaces.

Definition 1.1. *Let X and Y be two nonempty compact metric spaces. Their Gromov-Hausdorff distance $d(X, Y)$ is the infimum of $d_H^{Z'}(X', Y')$ over all metric spaces Z' and all subsets X' and Y' of Z' which are isometric respectively to X and Y.*

Note that the infimum in this definition makes sense: it is always possible to embed isometrically X and Y in a common metric space (for instance by putting a suitable distance on the disjoint union of X and Y).

Let $\mathcal{GH}$ denote the "space" of nonempty compact metric spaces up to isometry. There is a set-theoretic difficulty here, to which we will come back in Section 3 but that we will ignore for now.

The basic result in the theory is the following theorem, which we have formalized in the Lean proof assistant as part of the `mathlib` library.

Theorem 1.2. *The Gromov-Hausdorff distance is indeed a distance on $\mathcal{GH}$. With this distance, $\mathcal{GH}$ is a complete second countable metric space.*

Let us highlight two important points in this theorem that will be relevant later on.

- If two spaces are at distance zero, the theorem asserts that they are isometric. This is not obvious as the Gromov-Hausdorff distance is defined as an infimum. This result follows from the more general fact that the Gromov-Hausdorff distance between two spaces X and Y is always realized, i.e., the aforementioned infimum is in fact a minimum. To prove this, one should *construct* a metric space Z' and two isometric embeddings $f : X \to Z'$ and $g : Y \to Z'$ with $d_H^{Z'}(f(X), g(Y)) = d(X, Y)$.

- Given a Cauchy sequence X_n of compact metric spaces (for instance a sequence such that $d(X_n, X_{n+1}) \le 2^{-n}$), the theorem asserts that there exists a compact metric space X_∞ such that $X_n \to X_\infty$. Again, this statement involves the *construction* of the limiting space X_∞.

The standard setting for discussing convergence of random objects in probability theory is that of complete second countable metric spaces (see [Bil99]). Thanks to Theorem 1.2, this means that a theory of convergence of random compact metric spaces can be set up, and indeed it has become ubiquitous in modern probability theory. Let us just mention Aldous' continuous random tree [Ald91], which informally speaking is a random compact metric space which is almost-surely a (real) tree, but which formally is given by a probability measure on the space $\mathcal{GH}$. It roughly plays for random metric spaces the same universal role as Brownian motion does for random walks. The above framework makes it possible to say rigorously that a family of random metric spaces converges in distribution to the continuous random tree. This notion shows up in the author's mathematical research, and is his original motivation to formalize the Gromov-Hausdorff space in a proof assistant, as a step in his (unrealistic) program to formalize his own research results.

2 Formalization overview

Formalizing the Gromov-Hausdorff space is an interesting task because of the unusual feature that it is a "space" of equivalence classes of spaces (with quotation marks around the first space because of set-theoretic issues). A usable formalization in a mathematics library should retain the following properties:

1. It should interact well with preexisting topological concepts. In other words, if there is a standard notion of compact topological space X in the library, then one should be able to talk of the Gromov-Hausdorff distance between such spaces X and Y, and not between new gadgets that would have been defined specifically in view of this formalization.

2. The resulting Gromov-Hausdorff space should also be a topological space in the standard sense of the library.

3. One should be able to define a function mapping a nonempty compact metric space (in the usual sense) to an element of the Gromov-Hausdorff space.

These constraints seem hard to satisfy in simple type theory, where it is not possible to define a function whose arguments are types (the compact space X) and whose images are elements of another type (the Gromov-Hausdorff space). On the other hand, they should not be a problem for a framework based on dependent type theory, with an expressive enough mathematical library. Our formalization is done using the Lean theorem prover, based on a version of the calculus of inductive construction, in the framework of the `mathlib` library. It satisfies the above requirements. The main results are available in the `mathlib` file `topology/metric_space/gromov_hausdorff.lean`.

Let us give the form of the interface, i.e., the main definitions and statements, leaving implementation or proof details in ... blocks, before getting to more details.

```
definition GH_space : Type := ...

instance : metric_space GH_space := ...

instance : second_countable_topology GH_space := ...

instance : complete_space GH_space := ...

/-- Mapping a nonempty compact metric space to its equivalence class in `GH_space`. -/
definition to_GH_space (X : Type u) [metric_space X] [compact_space X] [nonempty X] : GH_space := ...

/-- Two nonempty compact spaces have the same image in `GH_space` if and only if they are isometric. -/
theorem to_GH_space_eq_to_GH_space_iff_isometric {X : Type u} [metric_space X] [compact_space X]
  [nonempty X] {Y : Type v} [metric_space Y] [compact_space Y] [nonempty Y] :
  to_GH_space X = to_GH_space Y ↔ nonempty (X ≃ᵢ Y) := ...

/-- The Gromov−Hausdorff distance between two spaces `X` and `Y` can be realized by
isometric embeddings into ` ℓ_infty_ℝ`. -/
theorem GH_dist_eq_Hausdorff_dist (X : Type u) [metric_space X] [compact_space X] [nonempty X]
  (Y : Type v) [metric_space Y] [compact_space Y] [nonempty Y] :
  ∃ Φ : X → ℓ_infty_ℝ, ∃ Ψ : Y → ℓ_infty_ℝ, isometry Φ ∧ isometry Ψ ∧
  GH_dist X Y = Hausdorff_dist (range Φ) (range Ψ) := ...
```

In this snippet, `GH_space` is a type formalizing the Gromov-Hausdorff space, i.e., the space of nonempty compact metric spaces up to isometry. It is endowed with a distance (the Gromov-Hausdorff distance) which turns it into a metric space, in the metric space instance. This metric space turns out to be second-countable and complete. The interface with concrete nonempty compact metric spaces is made through the function `to_GH_space`, associating to any nonempty compact metric space X its equivalence class in the Gromov-Hausdorff space. This definition is used in the form `to_GH_space X`: the assumptions of the form `[...]` in this definition are *typeclass assumptions* on X, registering that it is a nonempty compact metric space, and filled in automatically by the system when seeing an expression of the form `to_GH_space X`. The system raises an error if it can not deduce an instance for these from the context.

The relationship between concrete nonempty compact metric spaces and abstract points in the Gromov-Hausdorff space is illustrated with two theorems:

- `to_GH_space_eq_to_GH_space_iff_isometric` asserts that two spaces have the same image in the Gromov-Hausdorff space if and only if they are isometric;

- `GH_dist_eq_Hausdorff_dist` says that the Gromov-Hausdorff distance between two nonempty compact metric spaces is realized, i.e., one can embed them isometrically in a common metric space so that the Hausdorff distances between their images is exactly their Gromov-Hausdorff distance. The theorem is a little bit stronger, because it says that one can use as a common embedding space the metric space $\ell^\infty(\mathbb{R})$ of bounded real sequences, whatever the compact metric spaces X and Y. (See Section 3 for more on this).

Note that the former theorem is an easy consequence of the latter: if X and Y have zero Gromov-Hausdorff distance, then their images under Φ and Ψ given by the second theorem are at zero Hausdorff distance, hence they coincide, and it follows that $\Psi^{-1} \circ \Phi$ is an isometry between X and Y.

In the next three sections, we will give more details on three salient points of the formalization.

3 Formal definition of the Gromov-Hausdorff space

Until now, we have described the Gromov-Hausdorff space as the "space" of equivalence classes of compact metric spaces up to isometry. There is a problem here: we are quantifying over objects which are not constrained to belong to a given set. This kind of construction is not allowed in set theory, as it leads to Russell-like paradoxes: nonempty compact metric spaces form a class, not a set.

The type theory implemented by Lean makes it possible to circumvent this issue, thanks to the notion of universe level (already dating back to Russell). Informally speaking, any class at universe level u becomes an object one can manipulate at level $u + 1$, where u range over $\mathbb{N}$. Thus, one can define the type of all nonempty compact metric spaces in universe level u, as a well-defined type in universe level $u + 1$. Denote it with K_u. One can then define an equivalence relation $\sim$ on K_u, saying that two spaces are isometric, and construct a Gromov-Hausdorff space $\mathcal{GH}_u$ as $K_u/\sim$.

This definition has two drawbacks. First, it depends on the universe level u: one does not get one single Gromov-Hausdorff space, but infinitely many of them. This makes it more complicated to discuss the Gromov-Hausdorff distance of two nonempty compact spaces if they come from different universes. The second issue is that using universe levels for a construction is often not satisfactory to mathematicians: it means getting out of the standard ZFC framework by adding inaccessible cardinals axioms.

It turns out that the set theoretic issue that there is no set of all compact metric spaces is not a real issue. Indeed, the cardinality of a compact metric space is at most the cardinality of the continuum, which means that the number of non-isometric compact metric spaces is also controlled. For the formalization, this means that we can define one single Gromov-Hausdorff space, in the first universe `Type 0` (also called simply `Type`), the universe in which most natural objects such as $\mathbb{N}$ or $\mathbb{R}$ live. However, we can not just dismiss the issue as irrelevant, as is done in most textbooks: we have to make a sensible design choice.

We use the following classical proposition.

Proposition 3.1. *Consider a compact metric space X. There exists an isometric embedding of X into the space $\ell^\infty(\mathbb{R})$ of bounded real sequences with its distance coming from the sup norm.*

Proof. Let x_n be a dense sequence in X. To a point $x \in X$, associate the sequence $n \mapsto d(x, x_n)$. It is easy to check that this defines an isometric embedding of X into $\ell^\infty(\mathbb{R})$. $\square$

This embedding is called the Kuratowski embedding. From this proposition, it follows that all compact metric spaces have isometric representatives as subsets of $\ell^\infty(\mathbb{R})$. Therefore, we may *define* the Gromov-Hausdorff space as the space of all nonempty compact subsets of $\ell^\infty(\mathbb{R})$, up to isometry (taking advantage of the built-in quotient construction of Lean). This is an element of `Type 0` as announced, as all objects in this definition live in `Type 0`.

The map `to_GH_space`, assigning to an arbitrary nonempty compact metric space the corresponding point in `GH_space`, is then obtained by taking an isometric image of X in $\ell^\infty(\mathbb{R})$ thanks to Proposition 3.1, and then descending to the quotient `GH_space`.

4 The Gromov-Hausdorff distance is realized

Consider two nonempty compact metric spaces X and Y. A key point to show that the Gromov-Hausdorff distance is a distance is to show that there exist a metric space Z' and two isometric copies X' of X and Y' of Y inside Z' such that the Hausdorff distance $d_H^{Z'}(X', Y')$ is equal to the Gromov-Hausdorff distance $d(X, Y)$ of X and Y. One has always $d(X, Y) \leq d_H^{Z'}(X', Y')$, and the goal is to construct suitable Z' and X', Y' such that this inequality becomes an equality.

One can always find a sequence of spaces Z'_n and isometric embeddings $\Phi_n : X \to Z'_n$ and $\Psi_n : Y \to Z'_n$ such that $d_H^{Z'_n}(\Phi_n(X), \Psi_n(Y))$ converges to $d(X, Y)$, by definition of an infimum. The difficulty is that the spaces Z'_n are unrelated to each other, so making things converge by extracting subsequences has no obvious meaning.

The key idea is to forget completely Z'_n, and only remember its distance. Define a map Θ_n from the disjoint union $X \sqcup Y$ to Z'_n, equal to Φ_n on X and to Ψ_n on Y. Define a function d_n on $(X \sqcup Y)^2$ by $d_n(a, b) = d(\Theta_n(a), \Theta_n(b))$, where the distance on the right hand side is the distance in Z'_n. This is almost a distance on $X \sqcup Y$, coinciding with the original distances on X and on Y, except that it does not satisfy in general $d_n(a, b) = 0 \Rightarrow a = b$ since different points in X and Y may be mapped to the same point in Z'_n.

We claim that d_n has a subsequence which converges uniformly to a function d_∞ (which is also almost a distance in the previous sense). Define a space Z to be the quotient of $X \sqcup Y$ identifying two points a and b when

$d_\infty(a, b) = 0$. This is a metric space, in which X and Y embed isometrically and realizing the Gromov-Hausdorff distance by construction.

It remains to check the claim. This is a consequence of the classical Arzela-Ascoli theorem:

Theorem 4.1. *Let $f_n : X \to Z$ be a sequence of bounded continuous functions on a compact space X, with range included in a compact subset of the metric space Z. Assume that the functions f_n are equicontinuous: for every $x \in X$ and every $\epsilon > 0$, there exists a neighborhood U of x such that for every $n \in \mathbb{N}$ and every $y \in U$, one has $d(f_n(y), f_n(x)) \le \epsilon$. Then f_n admits a uniformly converging subsequence.*

Indeed, one checks readily that the family of functions d_n on the compact space $(X \sqcup Y)^2$ is equicontinuous (it is even uniformly Lipschitz-continuous). Unfortunately,the Arzela-Ascoli theorem was not available in `mathlib` at the time of the formalization of the Gromov-Hausdorff space (and neither was the notion of uniform convergence!). An important part of this formalization was therefore devoted to all these prerequisites, including the definition and study of the Banach space of bounded continuous functions on a topological space.

It is worth pointing out that, since then, these results have been put to good use in completely different directions in `mathlib` (for instance to formalize the Stone-Weierstrass theorem, asserting that an algebra of continuous functions separating points on a compact space is dense in the space of continuous functions). This is an important point of the formalization of fairly specialized concepts such as the Gromov-Hausdorff space: it is a way to notice general-purpose gaps in the library and to fill them. The `mathlib` philosophy is that these gaps should not be filled just in the minimal way needed to prove the target theorem, but in the maximal possible generality to make it suitable for further uses in different directions. For instance, during the formalization of the Gromov-Hausdorff distance, the notion of uniform convergence has been defined in the maximal generality of uniform spaces, even if we only needed the case of metric spaces for this specific application.

5   Completeness of the Gromov-Hausdorff space

To prove the completeness of the Gromov-Hausdorff space, we will need to glue metric spaces along isometric subspaces, as follows. Assume that Y and Z are two metric spaces, and that another metric space X admits two isometric embeddings $\Phi : X \to Y$ and $\Psi : X \to Z$. Then one can form a new space by identifying the two X subsets in Y and Z, and this new space is naturally a metric space, containing isometric copies of both Y and Z.

Let us now explain why the Gromov-Hausdorff space is complete. It is enough to show that a sequence of compact spaces satisfying $d(X_n, X_{n+1}) \le 2^{-n}$ converges. The difficulty is that we need to construct in some way the limiting metric space. The idea is to embed simultaneously all the X_n in a common metric space Z_∞, with controlled mutual Hausdorff distances, and use the fact the space of subsets of Z_∞, with the Hausdorff distance, is complete, to get the desired limit at a subset of Z_∞.

There exists for each n a metric space Y_n containing isometric copies of X_{n-1} and of X_n which are at Hausdorff distance $\le 2^{-n}$, by Section 4. Let us now define inductively a sequence of metric spaces Z_n containing isometric copies of $X_0, \ldots, X_n$, as follows.

1. Start with $Z_0 = X_0$.

2. Assume Z_n is defined. It contains an isometric copy of X_n. So does Y_{n+1}. Therefore, we may glue Z_n and Y_{n+1} along their respective copies of X_n, to obtain the new space Z_{n+1}. It contains a copy of X_{n+1} (the one contained in Y_{n+1}) and copies of $X_0, \ldots, X_n$ (the ones contained in Z_n).

Define a suitable limit Z_∞ of the increasing family Z_n (formally, an inductive limit). It is a metric space, containing for each k a copy X'_k of X_k. By construction, the Hausdorff distance $d_H^{Z_\infty}(X'_k, X'_{k+1})$ is $\le 2^{-k}$. Since, on a given complete metric space, the space of its compact subsets is a complete space for the Hausdorff distance, it follows that X'_k converges, to a compact subset X'_∞ of Z_∞. Then, in the Gromov-Hausdorff space, X_n converges to the class of X'_∞.

There is an interesting feature in the formalization of this proof, in the inductive definition of the space Z_n, highlighting several shortcomings of Lean 3. One should define simultaneously the space Z_n, but also a metric space structure on it, and an isometric embedding of X_n in Z_n (which only makes sense given the metric space structure). And the next step of the construction will take advantage of all these data to proceed. The most natural formalization would be by several mutually inductive definitions, but Lean 3 has weaknesses in this area. Instead, we used one single structure containing all these data, and one big induction to define the structure at

step $n+1$ from the structure at step n. Another issue is that the Lean 3 equation compiler generates a definition in terms of bounded recursion which is not easy to use. We use instead a direct definition in terms of the recursor for natural numbers. Here is the full inductive definition we use.

```
variables (X : ℕ → Type) [∀ n, metric_space (X n)] [∀ n, compact_space (X n)] [∀ n, nonempty (X n)]

/-- Auxiliary structure used to glue metric spaces below, recording an isometric embedding
of a type 'A' in another metric space. -/
structure aux_gluing_struct (A : Type) [metric_space A] : Type 1 :=
(space  : Type)
(metric : metric_space space)
(embed  : A → space)
(isom   : isometry embed)

/-- Auxiliary sequence of metric spaces, containing copies of 'X 0', ..., 'X n', where each
'X i' is glued to 'X (i+1)' in an optimal way. The space at step 'n+1' is obtained from the space
at step 'n' by adding 'X (n+1)', glued in an optimal way to the 'X n' already sitting there. -/
def aux_gluing (n : ℕ) : aux_gluing_struct (X n) := nat.rec_on n
  { space  := X 0,
    metric := by apply_instance,
    embed  := id,
    isom   := λ x y, rfl }
(λ n Z, by letI : metric_space Z.space := Z.metric; exact
  { space  := glue_space Z.isom (isometry_optimal_GH_injl (X n) (X (n+1))),
    metric := by apply_instance,
    embed  := (to_glue_r Z.isom (isometry_optimal_GH_injl (X n) (X (n+1))))
                ∘ (optimal_GH_injr (X n) (X (n+1))),
    isom   := (to_glue_r_isometry _ _).comp (isometry_optimal_GH_injr (X n) (X (n+1))) })
```

We start from a context in which a sequence of nonempty compact metric spaces X_n is given, which we want to glue together. The structure `aux_gluing_struct A` records a metric space containing an isometric copy of a metric space A. The definition `aux_gluing n` constructs inductively over n a metric space containing an isometric copy of X_n (and also of all the previous ones, by design, but we only register the last one for the inductive construction). For $n = 0$, it is just X_0. At the $(n + 1)$-th step, it glues two spaces containing an isometric copy of X_n along X_n as explained in Section 4: on the one hand the space constructed at the previous step; on the other hand a space in which the Gromov-Hausdorff distance between X_n and X_{n+1} is realized.

The reader may note the line `letI : metric_space Z.space := Z.metric` at the beginning of the inductive step in the construction. By induction, the space `Z.space` constructed at step n has a metric space structure, called `Z.metric`. However, this metric space structure is not yet available to typeclass inference: there is a caching mechanism underneath (which is very important performancewise as typeclass inference is quite costly), so new instances need to be declared explicitly just like here. Once this preliminary incantation has been done, the system knows about the metric space structure on `Z.space` and is happy with the statement that a map to `Z.space` is an isometry, for instance. This is needed for the next step of the construction to go through.

Once this inductive definition has been set up properly (together with enough properties of the gluing of metric spaces, and of inductive limits of metric spaces), the rest can be formalized without any specific difficulty.

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