The Homotopy Lifting Theorem

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Oberwolfach, November 2, 2012

Conventions

"Space" $=$ "compact metrizable space."

"Map" $=$ "continuous function."

"Subspace" $=$ (usually) "closed subspace."

"Space pair" will mean a pair (Y, Z), where Y is a space and Z a (closed) subspace.

"Ideal" $=$ "two-sided ideal."

Definition:

A space X is an *absolute neighborhood retract* (ANR) if, whenever (Y, Z) is a space pair, and $\phi : Z \to X$ is a map, then ϕ extends to a map $\psi : U \to X$ for some neighborhood U of Z.

Examples: (compact) manifolds with boundary, polyhedra

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Examples: (compact) manifolds with boundary, polyhedra

Proposition:

A space X is an ANR if and only if, whenever Y is a space and (Z_n) a decreasing sequence of closed subspaces with $Z = \cap_n Z_n$, and $\phi : Z \to X$ is a map, then ϕ extends to a map $\psi : Z_n \to X$ for some sufficiently large n.

The Borsuk Homotopy Extension Theorem

Theorem:

Let X be an ANR, (Y, Z) a space pair, (ϕ_t) $(0 \leq t \leq 1)$ a uniformly continuous path of maps from Z to X (i.e. $h(t, z) = \phi_t(z)$ is a homotopy from ϕ_0 to ϕ_1). Suppose ϕ_0 extends to a map $\bar{\phi}_0$ from Y to X. Then there is a uniformly continuous path $\bar{\phi}_t$ of extensions of the ϕ_t to functions from Y to X (i.e. $\bar{h}(t, y) = \bar{\phi}_t(y)$ is a homotopy from $\bar{\phi}_0$ to $\bar{\phi}_1$). In particular, ϕ_1 extends to Y.

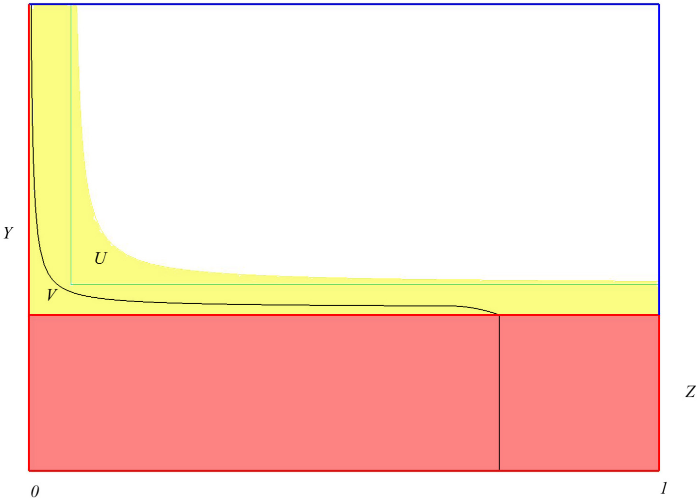
"Universal cofibration property" for maps into X.

Idea of Proof

Let $\tilde{Y} = [0,1] \times Y$, $\tilde{Z} = (\{0\} \times Y) \cup ([0,1] \times Z)$.

Dowker's Lemma:

Inside any neighborhood U of $\tilde{Z}$ in $\tilde{Y}$ is a subspace containing $\tilde{Z}$ which is homeomorphic to $\tilde{Y}$ under a homeomorphism which is the identity on $\tilde{Z}$.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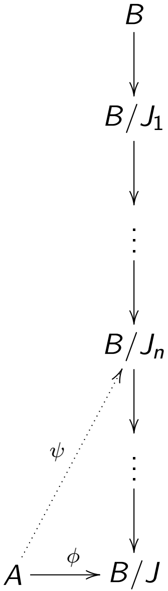
Semiprojective C*-Algebras

When the alternate characterization of ANR's is rephrased by "turning the arrows around," we obtain the definition of a semiprojective C*-algebra:

Definition:

A separable C*-algebra A is *semiprojective* if, whenever B is a C*-algebra, (J_n) an increasing sequence of closed ideals of B with $J = [\cup_n J_n]^-$, and $\phi : A \to B/J$ is a *-homomorphism, there is a *-homomorphism $\psi : A \to B/J_n$ for some sufficiently large n, such that $\phi = \pi_J \circ \psi$. The map ψ is called a *partial lift* of ϕ.


B
B/J_1
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SEMIPROJECTIVITY
UP THE STAIRS

Examples:
Finite-dimensional C*-algebras
$C([0,1])$, $C(\mathbb{T})$
The Toeplitz algebra, Cuntz and Cuntz-Krieger algebras
The dimension-drop algebras $\mathbb{I}_{p,q}$
$+$ many more!

The definition of semiprojectivity can be made in any category of (separable) C*-algebras. Obviously, $C(X)$ is semiprojective in the category of unital commutative C*-algebras if and only if X is an ANR. But if X is an ANR, $C(X)$ is not necessarily semiprojective in the category of all separable C*-algebras.

Example: Commutation relations are not generally partially liftable. In fact, $C([0,1]^2)$ is not semiprojective, even though $[0,1]^2$ is an ANR.

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Theorem (Sørensen-Thiel):

$C(X)$ is semiprojective in the category of general separable C*-algebras if and only if X is an ANR with $dim(X) \leq 1$.

Some results about ANR's, with arrows reversed, are true for semiprojective C*-algebras because the same proof with arrows reversed is valid in the noncommutative case.

Useful example:

Theorem:

Let A be a semiprojective, $(B_n, \beta_{n,m})$ an inductive system of C*-algebras, with $B = \lim_{\rightarrow}(B_n, \beta_{n,m})$. If $\phi : A \rightarrow B$ is a *-homomorphism, then for all sufficiently large n there is a *-homomorphism $\psi_n : A \rightarrow B_n$ such that, if $\phi_n = \beta_n \circ \psi_n$, then $\phi_n \rightarrow \phi$ in the point-norm topology and $\phi_n \simeq \phi$.

Here $\beta_n : B_n \rightarrow B$ is the natural map induced by the inductive system. (The connecting maps in the inductive system do not have to be injective.)

Stable Relations

There is a theory of universal C*-algebras on a set of generators and relations. Relations are typically algebraic relations, or more generally of the form

$$\|p(x_{i_1},\dots,x_{i_n},x_{i_1}^*,\dots,x_{i_n}^*)\| \leq \eta$$

where p is a polynomial in $2n$ noncommuting variables.

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In a semiprojective C*-algebra, relations are "stable": if A is semiprojective and is the universal C*-algebra on a finite set $\{x_1, \ldots, x_n\}$ of generators and a set $\mathcal{R}$ of relations, and $\{y_1, \ldots, y_n\}$ is a set of elements in a C*-algebra B which approximately satisfy the relations, then the y_j can be moved a small amount to elements $z_1, \ldots, z_n$ in B which exactly satisfy the relations.

So semiprojective C*-algebras are "flexible" in the sense that an approximate homomorphism into another C*-algebra can be "corrected" to an exact homomorphism.

The Homotopy Lifting Theorem

Corresponding statement for semiprojective C*-algebras:

Theorem:

Let A be a semiprojective C*-algebra, B a C*-algebra, I a closed ideal of B, (ϕ_t) $(0 \leq t \leq 1)$ a point-norm continuous path of *-homomorphisms from A to B/I. Suppose ϕ_0 lifts to a *-homomorphism $\bar{\phi}_0 : A \to B$, i.e. $\pi_I \circ \bar{\phi}_0 = \phi_0$. Then there is a point-norm continuous path $(\bar{\phi}_t)$ $(0 \leq t \leq 1)$ of *-homomorphisms from A to B beginning at $\bar{\phi}_0$ such that $\bar{\phi}_t$ is a lifting of ϕ_t for each t, i.e. the entire homotopy lifts. In particular, ϕ_1 lifts to a *-homomorphism from A to B.

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The commutative proof has no hope of working in the noncommutative case. We need a different approach.


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The General Chinese Remainder Theorem

Proposition:

Let R be a ring, and I and J ideals in R. Then the map

$$\phi : a \mapsto (a \bmod I, a \bmod J)$$

gives an isomorphism from $R/(I \cap J)$ onto the fibered product

$$P = \{(x, y) : x \in R/I, y \in R/J, \pi_1(x) = \pi_2(y)\} \subseteq (R/I) \oplus (R/J)$$

where $\pi_1 : R/I \to R/(I + J)$ and $\pi_2 : R/J \to R/(I + J)$ are the quotient maps.

P is the pullback of (π_1, π_2).

The usual Chinese Remainder Theorem is the special case where $I + J = R$, where P is just the direct sum $R/I \oplus R/J$.

In particular, to define a homomorphism from another ring into $R/(I \cap J)$, it suffices to give a compatible pair of homomorphisms into R/I and R/J.

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In the case $R = C(X)$, and (closed) ideals I and J correspond to closed sets Y and Z, there is a one-one correspondence between maps from $Y \cup Z$ to $\mathbb{C}$ and pairs (g, h), where $g : Y \to \mathbb{C}$ and $h : Z \to \mathbb{C}$ are maps which agree on $Y \cap Z$.

Partial Liftings with Specified Quotient

If B is a C*-algebra, (J_n) an increasing sequence of closed ideals of B, and $J = [\cup J_n]^-$, and A is a semiprojective C*-algebra, then any homomorphism $\phi : A \to B/J$ can be partially lifted to a homomorphism $\psi : A \to B/J_n$ for some sufficiently large n.

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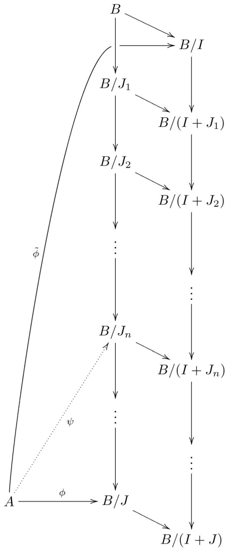
But suppose we also have another closed ideal I of B and a homomorphism $\tilde{\phi}$ from A to B/I such that ϕ and $\tilde{\phi}$ agree mod $I + J$. Can we partially lift ϕ to ψ so that ψ agrees with $\tilde{\phi}$ mod $I + J_n$?


B
B/I
B/J_1
$B/(I+J_1)$
B/J_2
$B/(I+J_2)$
$\tilde{\phi}$
B/J_n
$B/(I+J_n)$
ψ
A
ϕ
B/J
$B/(I+J)$

Theorem:

Let A be a semiprojective C*-algebra, B a C*-algebra, (J_n) an increasing sequence of closed ideals of B with $J = [\cup J_n]^-$, I another closed ideal of B, and $\phi : A \to B/J$ and $\tilde{\phi} : A \to B/I$ *-homomorphisms with $\pi_{I+J} \circ \phi = \pi_{I+J} \circ \tilde{\phi}$. Then for some sufficiently large n there is a *-homomorphism $\psi : A \to B/J_n$ such that $\pi_J \circ \psi = \phi$ and $\pi_{I+J_n} \circ \psi = \pi_{I+J_n} \circ \tilde{\phi}$.

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If X is an ANR, Y a space, Z_n a decreasing sequence of closed subspaces with $Z = \cap_n Z_n$, W another closed subspace, and $\phi : Z \to X$ and $\tilde{\phi} : W \to X$ are maps which agree on $Z \cap W$, then ϕ can be extended to $\psi : Z_n \to X$ for some n so that ψ agrees with $\tilde{\phi}$ on $Z_n \cap W$.
[Note that $Z \cup W = \cap_n (Z_n \cup W)$.]

By the Chinese Remainder Theorem ϕ and $\tilde{\phi}$ define a homomorphism $\bar{\phi}$ from A to $B/(I \cap J)$, which partially lifts to a homomorphism $\bar{\psi}$ from A to $B/(I \cap J_n)$ for some n by semiprojectivity. The map $\bar{\psi}$ defines compatible homomorphisms $\psi : A \to B/J_n$ and $\tilde{\psi} : A \to B/I$. But we have $\tilde{\psi} = \tilde{\phi}$ since the reduction from $B/(I \cap J_n)$ to B/I factors through $B/(I \cap J)$, where $\bar{\psi}$ becomes $\bar{\phi}$.

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Technicality: It is not obvious that $\cup_n(I \cap J_n)$ is dense in $I \cap J$, but this follows from the uniqueness of norm on a C*-algebra.

Lifting Close Homomorphisms

If A and B are C*-algebras and I is a closed ideal of B, then a homomorphism from A to B/I need not lift in general to a homomorphism from A to B, even if A is semiprojective. But suppose $\phi : A \to B/I$ does lift to $\bar{\phi} : A \to B$, and ψ is another homomorphism from A to B/I which is close to ϕ in the point-norm topology. If A is semiprojective, does ψ also lift to B, and can the lift be chosen close to $\bar{\phi}$ in the point-norm topology? The answer is yes in the commutative category, but the commutative proof does not generalize to the noncommutative case. However, we can by a different argument obtain the same result for general semiprojective C*-algebras.

The next theorem is really the main result:

Theorem:

Let A be a semiprojective C*-algebra generated by a finite or countable set $\mathcal{G} = \{x_1, x_2, \dots\}$ with $\lim_{j\to\infty} \|x_j\| = 0$ if $\mathcal{G}$ is infinite. Then for any $\epsilon > 0$ there is a $\delta > 0$ such that, whenever B is a C*-algebra, I a closed ideal of B, ϕ and ψ *-homomorphisms from A to B/I with $\|\phi(x_j) - \psi(x_j)\| < \delta$ for all j and such that ϕ lifts to a *-homomorphism $\bar{\phi} : A \to B$ (i.e. $\pi_I \circ \bar{\phi} = \phi$), then ψ also lifts to a *-homomorphism $\bar{\psi} : A \to B$ with $\|\bar{\psi}(x_j) - \bar{\phi}(x_j)\| < \epsilon$ for all j. (The δ depends on ϵ, A, and the set $\mathcal{G}$ of generators, but not on the B, I, ϕ, ψ.)

Outline of Proof

If the statement is false, then there is an $\epsilon > 0$ such that there are B_n, I_n, ϕ_n, ψ_n with

$$\|\phi_n(x_j) - \psi_n(x_j)\| < \frac{1}{n}$$

for all n and j, such that ϕ_n lifts but ψ_n does not. Let $B = \prod_n B_n$, $I = \prod_n I_n$, J_n the ideal of elements of B vanishing after the n'th term, $J = [\cup J_n]^- = \oplus_n B_n$. Let $\bar{\phi} : A \to B$ be defined by

$$\bar{\phi}(x) = (\bar{\phi}_1(x), \bar{\phi}_2(x), \dots)$$

and let $\phi = \pi_J \circ \bar{\phi} : A \to B/J$. There is also a homomorphism $\tilde{\phi}$ from A to $B/I \cong \prod_n (B_n/I_n)$ defined by

$$\tilde{\phi}(x) = (\psi_1(x), \psi_2(x), \dots) .$$

Then ϕ cannot be lifted to B/J_n compatibly with $\tilde{\phi}$, contradiction.

The Homotopy Lifting Theorem Again

Theorem:

Let A be a semiprojective C*-algebra, B a C*-algebra, I a closed ideal of B, (ϕ_t) $(0 \leq t \leq 1)$ a point-norm continuous path of *-homomorphisms from A to B/I. Suppose ϕ_0 lifts to a *-homomorphism $\bar{\phi}_0 : A \to B$, i.e. $\pi_I \circ \bar{\phi}_0 = \phi_0$. Then there is a point-norm continuous path $(\bar{\phi}_t)$ $(0 \leq t \leq 1)$ of *-homomorphisms from A to B beginning at $\bar{\phi}_0$ such that $\bar{\phi}_t$ is a lifting of ϕ_t for each t, i.e. the entire homotopy lifts. In particular, ϕ_1 lifts to a *-homomorphism from A to B.

Proof of the Homotopy Lifting Theorem

Let $\mathcal{G} = \{x_1, x_2, \dots\}$ be a countable set of generators for A, with $\|x_j\| \to 0$. Fix $\epsilon > 0$, say $\epsilon = 1$, and fix $\delta > 0$ satisfying the conclusion of the previous theorem for ϵ, A, $\mathcal{G}$.

Choose a finite partition $0 = t_0 < t_1 < t_2 < \cdots < t_m = 1$ such that $\|\phi_s(x_j) - \phi_t(x_j)\| < \delta$ for all j whenever $s, t \in [t_{i-1}, t_i]$ for any i. There is such a partition since one only needs to consider finitely many x_j, the condition being automatic for any x_j with $\|x_j\| < \frac{\delta}{2}$.

Begin with $[0, t_1]$. Let $\tilde{B} = C([0, t_1], B)$, and J the ideal of $\tilde{B}$ consisting of functions $f : [0, t_1] \to I$ with $f(0) = 0$. Then

$$\tilde{B}/J \cong \{(f, b) \in C([0, t_1], B/I) \oplus B : f(0) = \pi_I(b)\} .$$

Define homomorphisms $\phi, \psi : A \to \tilde{B}/J$ by setting $\phi(x) = (f_x, \bar{\phi}_0(x))$, where $f_x(t) = \phi_0(x)$ for all t, and $\psi(x) = (g_x, \bar{\phi}_0(x))$, where $g_x(t) = \phi_t(x)$ for all t. We then have

$$\|\phi(x_j) - \psi(x_j)\| < \delta$$

for all j. Since ϕ lifts to a *-homomorphism from A to $\tilde{B}$ (e.g. by the constant function $\bar{\phi}_0$), ψ also lifts, defining a continuous path of lifts $(\bar{\phi}_t)$ of the ϕ_t for $0 \leq t \leq t_1$.

Now repeat the process on $[t_1, t_2]$, using the lift $\bar{\phi}_{t_1}$ as the starting point, and continue through all the intervals. After a finite number of steps the entire homotopy is lifted.

ℓ-Open and ℓ-Closed C*-Algebras

If A and B are C*-algebras, denote by $\mathrm{Hom}(A, B)$ the set of *-homomorphisms from A to B, endowed with the point-norm topology. $\mathrm{Hom}(A, B)$ is separable and metrizable (if A and B are separable). If A and B are unital, let $\mathrm{Hom}_1(A, B)$ be the set of unital *-homomorphisms from A to B. $\mathrm{Hom}_1(A, B)$ is a clopen subset of $\mathrm{Hom}(A, B)$ (since a projection close to the identity in a C*-algebra is equal to the identity).

If $A = C(X)$ and $B = C(Y)$, then $\mathrm{Hom}_1(A, B)$ is naturally homeomorphic to X^Y, the set of continuous functions from Y to X, endowed with the topology of uniform convergence (with respect to any fixed metric on X, or with respect to the unique uniform structure on X compatible with its topology).

If $\mathcal{C}$ is a category of C*-algebras, $A, B \in \mathcal{C}$, and I is a closed ideal of B, denote by $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ the set of $\mathcal{C}$-morphisms from A to B/I which lift to $\mathcal{C}$-morphisms from A to B. $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ is a subset of $\mathrm{Hom}_{\mathcal{C}}(A, B/I)$.

If $\mathcal{C}$ is the category of separable unital commutative C*-algebras and $A = C(X)$, $B = C(Y)$, with X, Y compact metrizable spaces, I corresponds to a closed subset Z of Y and $B/I \cong C(Z)$; then $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ is the subset $X^{Z\uparrow Y}$ of X^Z consisting of maps from Z to X which extend to maps from Y to X.

Question: When is $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ open or closed in $\mathrm{Hom}_{\mathcal{C}}(A, B/I)$?

Examples show it is neither open nor closed in general. We seek conditions on A insuring that $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ is always open or closed in $\mathrm{Hom}_{\mathcal{C}}(A, B/I)$ for any B and I.

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Definition:

Let $\mathcal{C}$ be a category, and $A \in \mathcal{C}$.

(i) A is *ℓ-open* (in $\mathcal{C}$) if, for every pair (B, I) in $\mathcal{C}$, the set $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ is open in $\mathrm{Hom}_{\mathcal{C}}(A, B/I)$.

(ii) A is *ℓ-closed* (in $\mathcal{C}$) if, for every pair (B, I) in $\mathcal{C}$, the set $\mathrm{Hom}_{\mathcal{C}}(A, B, I)$ is closed in $\mathrm{Hom}_{\mathcal{C}}(A, B/I)$.

If $\mathcal{C}$ is the category of all separable C*-algebras, we just say A is ℓ-open [ℓ-closed].

Corresponding notion for spaces:

Definition:

Let X be a space.

(i) X is *e-open* if, for every space pair (Y, Z), the set $X^{Z\uparrow Y}$ is open in X^Z.

(ii) X is *e-closed* if, for every space pair (Y, Z), the set $X^{Z\uparrow Y}$ is closed in X^Z.

If $\mathcal{C}$ is the category of separable unital commutative C*-algebras and $A = C(X)$, then A is ℓ-open [ℓ-closed] in $\mathcal{C}$ if and only if X is e-open [e-closed].
But X e-open [e-closed] does not obviously imply that $C(X)$ is ℓ-open [ℓ-closed] in the general category.

Example

Let $N = \{0\} \cup \left\{\frac{1}{n} : n \in \mathbb{N}\right\} \subseteq [0,1]$. Then N is not an ANR since no neighborhood in $[0,1]$ retracts.

The space N is *e*-closed but not *e*-open.

To show N is not *e*-open, take $Y = [0,1]$ and $Z = N$. Define $\phi_n : N \to N$ by

$$\phi_n\left(\frac{1}{k}\right) = \frac{1}{k+n}$$

and $\phi_n(0) = 0$. Then no ϕ_n is extendible to Y. But (ϕ_n) converges uniformly to a constant function, which obviously extends.

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and $\phi_n(0) = 0$. Then no ϕ_n is extendible to Y. But (ϕ_n) converges uniformly to a constant function, which obviously extends.

The argument that N is e-closed is more complicated.

More Examples

(i) If X is a space with a path component which is not closed (e.g. the topologist's sine curve or a solenoid), then X is not e-open or e-closed. Thus $C(X)$ is not ℓ-open or ℓ-closed.

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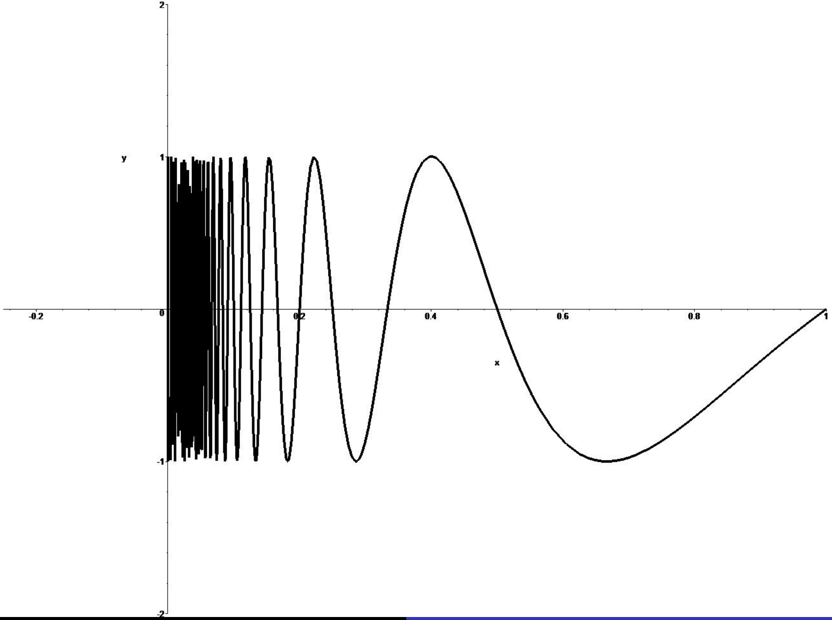
(ii) The infinite comb (which is path-connected and even contractible) is not e-open or e-closed.

In both cases use $Y = [0, 1]$,

$$Z = N = \{0\} \cup \left\{ \frac{1}{n} : n \in \mathbb{N} \right\} .$$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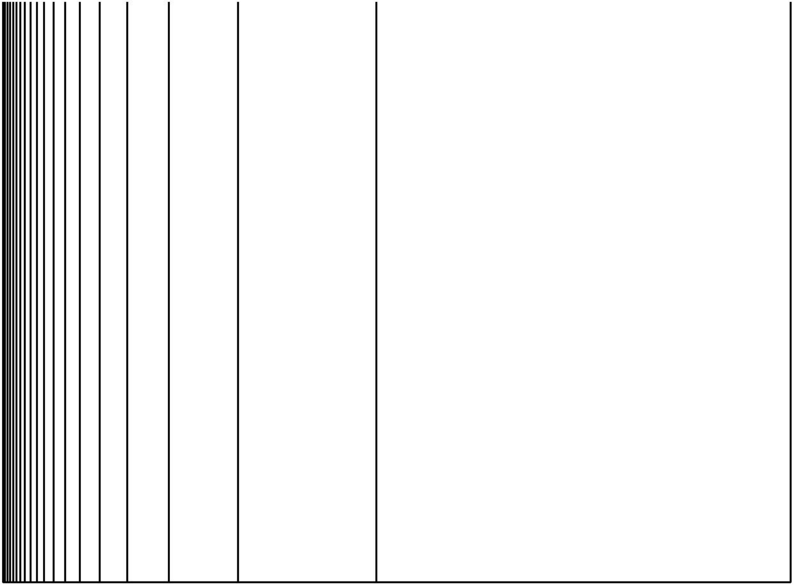

Easy corollary of the Close Lifting Theorem and its commutative counterpart:

Corollary:

(i) If A is a semiprojective C*-algebra, then A is both ℓ-open and ℓ-closed.

(ii) If X is an ANR, then X is both e-open and e-closed.

The converse is true in the commutative case for finite-dimensional spaces:

Theorem:

A finite-dimensional *e*-open space is an ANR.

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Theorem:

A finite-dimensional e-open space is an ANR.

The infinite-dimensional case is at least very nearly true.

So it is reasonable to conjecture:

Conjecture:

Every e-open space is an ANR. Every ℓ-open C*-algebra is semiprojective.

The ℓ-closed property (*e*-closed for spaces) is more mysterious.

Although there is no obvious direct proof that an ℓ-open C*-algebra is ℓ-closed, I do not know an example of a C*-algebra which is ℓ-open but not ℓ-closed (or of space which is *e*-open but not *e*-closed), and I conjecture that none exist. There are ℓ-closed C*-algebras which are not ℓ-open.

I do not have a good idea how to characterize ℓ-closed C*-algebras.

Examples

(i) Let A be the universal C*-algebra generated by a sequence of projections (the full free product of a countable number of copies of $\mathbb{C}$). Then A is ℓ-closed but not ℓ-open.

More generally, the full free product of a sequence of semiprojective C*-algebras is ℓ-closed, but not ℓ-open unless all but finitely many are projective.

(ii) Let A be the universal C*-algebra generated by a normal element x of norm ≤ 1. Then $A \cong C_0(\mathbb{D})$, the functions vanishing at $(0,0)$ on the closed unit disk $\mathbb{D}$ in $\mathbb{R}^2$. To show that A is not ℓ-open, let B be the Toeplitz algebra, $I = \mathbb{K}$, S the unilateral shift, s the image in B/I. Define $\phi_n : A \to B/I$ by sending x to $\frac{1}{n}s$. Then (ϕ_n) converges in the point-norm topology to the zero homomorphism, which obviously lifts to B. But no ϕ_n lifts.

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Showing that A is ℓ-closed is the same as solving (positively) the following problem: if B is a C*-algebra, I an ideal of B, and $\mathcal{N}$ the (closed) set of normal elements of B, is $\pi_I(\mathcal{N})$ always closed in B/I? This appears to be unknown.

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If this argument works, it can be slightly modified to show that the unitization $C(\mathbb{D})$ is ℓ-closed but not ℓ-open.

(iii) Consider the C*-algebras c of convergent sequences of complex numbers and c_0 of sequences of complex numbers converging to 0.

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The question whether c and c_0 are ℓ-closed (in the general category) is much more involved than in the commutative case. The commutative case is simpler since

(1) Close projections in a commutative C*-algebra are actually equal.
(2) A product of two commuting projections is a projection. In particular, if q is a projection in a quotient B/I, with B commutative, and p_1, p_2 are two projection lifts to B, then $p = p_1 p_2$ is also a projection lift to B with $p \leq p_1$, $p \leq p_2$. Nothing like this is true for general noncommutative B.

(iv) A key test algebra is $\mathbb{K}$. It is easy to show that $\mathbb{K}$ is not semiprojective. I am convinced that $\mathbb{K}$ is not ℓ-open, but I can't prove it yet (I have a construction using amalgamated free products that should work). I also don't know whether $\mathbb{K}$ is ℓ-closed; I suspect it is.

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Questions:

Are the C*-algebras in (ii)–(iv) ℓ-closed? Is $\mathbb{K}$ ℓ-open?