Computable categoricity relative to a degree

SIU Online Logic Seminar

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Outline

1. Notions of categoricity
2. Categoricity relative to a degree
   - Above $\mathbf{0}''$ and below $\mathbf{0}'$
   - Generalizing the DHM result
3. Extensions of current work
   - Embedding lattices
   - Categoricity relative to a generic degree
   - Focusing on structures
4. Proof sketch of the poset result

Notions of categoricity

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These notions are not equivalent in general. Gončarov [Gon77] built the first example of a structure which was computably categorical but *not* relatively computably categorical.

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Categoricity relative to a degree

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We first begin with the following result.

Fact (Downey, Harrison-Trainor, Melnikov [DHTM21])

If $\mathcal{A}$ is a computable structure and it is computably categorical relative to some degree $\mathbf{d} \geq \mathbf{0}''$, then $\mathcal{A}$ has a $\mathbf{0}''$-computable Σ^0_1 Scott family. In particular, $\mathcal{A}$ is computably categorical relative to all $\mathbf{d} \geq \mathbf{0}''$.

The cone above $0''$

We sketch the proof of this fact. We first need the following results.

Theorem (Ash, Knight, Manasse, and Slaman [Ash+89]; Chisholm [Chi90])

A structure is relatively computably categorical if and only if it has a formally Σ_1 Scott family.

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If a structure is computably categorical and its $\forall\exists$ theory is decidable, then it is relatively computably categorical.

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Theorem (Gončarov [Gon80] (relativized))

If a structure is computably categorical relative to $\mathbf{d}$ and its $\forall\exists$ theory is $\mathbf{d}$-decidable, then it has a Scott family of $\exists$-formulas that is c.e. in $\mathbf{d}$.

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The cone above $\mathbf{0}''$: proof sketch

Proof sketch.

(1) Suppose $\mathcal{A}$ is computably categorical relative to a degree $\mathbf{d} \geq \mathbf{0}''$. Since $\mathcal{A}$ is computable, its $\forall\exists$ diagram is computable from $\mathbf{0}''$ and hence from $\mathbf{d}$.

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(3) We can use $\mathbf{0}''$ to enumerate this Scott family of $\exists$-formulas, and so this is a formally Σ_1 Scott family relative to $\mathbf{0}''$.

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Using this Scott family, we can computably build isomorphisms, and so for every $\mathbf{d} \geq \mathbf{0}''$, $\mathcal{A}$ is computably categorical relative to $\mathbf{d}$. This fact implies that for *any* computable structure $\mathcal{A}$, either it is computably categorical relative to *all* degrees above $\mathbf{0}''$ or to *no* degree above $\mathbf{0}''$.

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There is a computable structure $\mathcal{A}$ *and c.e. degrees* $\mathbf{0} = \mathbf{d}_0 <_T \mathbf{e}_0 <_T \mathbf{d}_1 <_T \mathbf{e}_1 <_T \dots$ *such that*

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(1) *$\mathcal{A}$ is computably categorical relative to $\mathbf{d}_i$ for each i,*

(2) *$\mathcal{A}$ is not computably categorical relative to $\mathbf{e}_i$ for each i,*

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The structure they constructed to witness this was a directed graph.

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Theorem (V. [Vil24])

Let $P = (P, \leq)$ be a computable partially ordered set and let $P = P_0 \sqcup P_1$ be a computable partition. Then, there exists a computable directed graph $\mathcal{G}$ and an embedding h of P into the c.e. degrees where

(1) *$\mathcal{G}$ is computably categorical;*

(2) *$\mathcal{G}$ is computably categorical relative to each degree in $h(P_0)$; and*

(3) *$\mathcal{G}$ is not computably categorical relative to each degree in $h(P_1)$.*

Extensions of current work

Future directions: embedding a lattice

The techniques utilized in proving the poset result can also be combined with the usual techniques to construct minimal pairs.

Theorem (V. [Vil24])

There exists a computable computably categorical directed graph $\mathcal{G}$ and c.e. sets X_0 and X_1 such that

(1) *X_0 and X_1 form a minimal pair,*

(2) *$\mathcal{G}$ is not computably categorical relative to X_0 and to X_1, and*

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Question

Can you embed bigger distributive lattices into the c.e. degrees in a manner similar to the poset result?

Future directions: in the generic degrees

Definition

A degree **d** is **low for isomorphism** if for every pair of computable structures $\mathcal{A}$ and $\mathcal{B}$, $\mathcal{A} \cong_{\mathbf{d}} \mathcal{B}$ if and only if $\mathcal{A} \cong_{\Delta^0_1} \mathcal{B}$.

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Theorem (Franklin, Solomon [FS14])

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Every 2-generic degree is low for isomorphism.

This means that there *cannot* be a computable structure $\mathcal{A}$ which is not computably categorical but is computably categorical relative to $\mathbf{d}$ for a 2-generic degree $\mathbf{d}$.

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Theorem

There exists a (properly) 1-generic G such that there is a computable directed graph $\mathcal{A}$ where $\mathcal{A}$ is not computably categorical but is computably categorical relative to G.

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Theorem (Bazhenov [Baz14])

For every degree $\mathbf{d} < \mathbf{0}'$*, a computable Boolean algebra is* $\mathbf{d}$*-computably categorical if and only if it is computably categorical.*

Future directions: identifying pathological behavior in classes of structures

Corollary (from results in [Hir+02] and [Mil+18])

For the following classes of structures, there exists a computable example in each class which witnesses the behavior in the poset result:

(1) *symmetric, irreflexive graphs; partial orderings; lattices; rings with zero-divisors; integral domains of arbitrary characteristic; commutative semigroups; and 2-step nilpotent groups (by Theorem 1.22 of [Hir+02])*

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Currently, the full picture is yet to be determined for some classes of structures, such as linear orderings.

Proof sketch of the poset result

Notation

For $p \in P$, we build uniformly c.e. sets A_p.

Definition

For $p \in P$, we define the c.e. set

$$D_p = \bigoplus_{q \leq p} A_q.$$

Our embedding will be the map $h(p) = D_p$.

We also have the following notation for convenience.

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$$\overline{D_p} := \bigoplus_{q \neq p} A_q.$$

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- $\mathcal{M}_i^{D_p}$ is the ith (partial) D_p-computable graph with domain ω where $E(x, y) \iff \Phi_i^{D_p}(x, y) = 1$ and $\neg E(x, y) \iff \Phi_i^{D_p}(x, y) = 0$.

Requirements

We have the following requirements:

- $N_e^p : \Phi_e^{\overline{D_p}} \neq A_p$,
- S_e : if $\mathcal{G} \cong \mathcal{M}_e$, then there exists a computable isomorphism $f_e : \mathcal{G} \to \mathcal{M}_e$,
- for $p \in P_0$, T_i^p : if $\mathcal{G} \cong \mathcal{M}_i^{D_p}$, then there exists a D_p-computable isomorphism $g_i^{D_p} : \mathcal{G} \to \mathcal{M}_i^{D_p}$, and
- for $q \in P_1$, R_e^q : $\Phi_e^{D_q} : \mathcal{G} \to \mathcal{B}_q$ is not an isomorphism where $\mathcal{B}_q$ is a D_q-computable copy of $\mathcal{G}$ we build.

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The N_e^p requirements ensure that h is an embedding of P into the c.e. degrees. The S_e requirements ensure that $\mathcal{G}$ is computably categorical. The T_i^p requirements ensure that $\mathcal{G}$ is computably categorical relative to all degrees in $h(P_0)$. The R_e^q requirements ensure that $\mathcal{G}$ is not computably categorical relative to any degree in $h(P_1)$.

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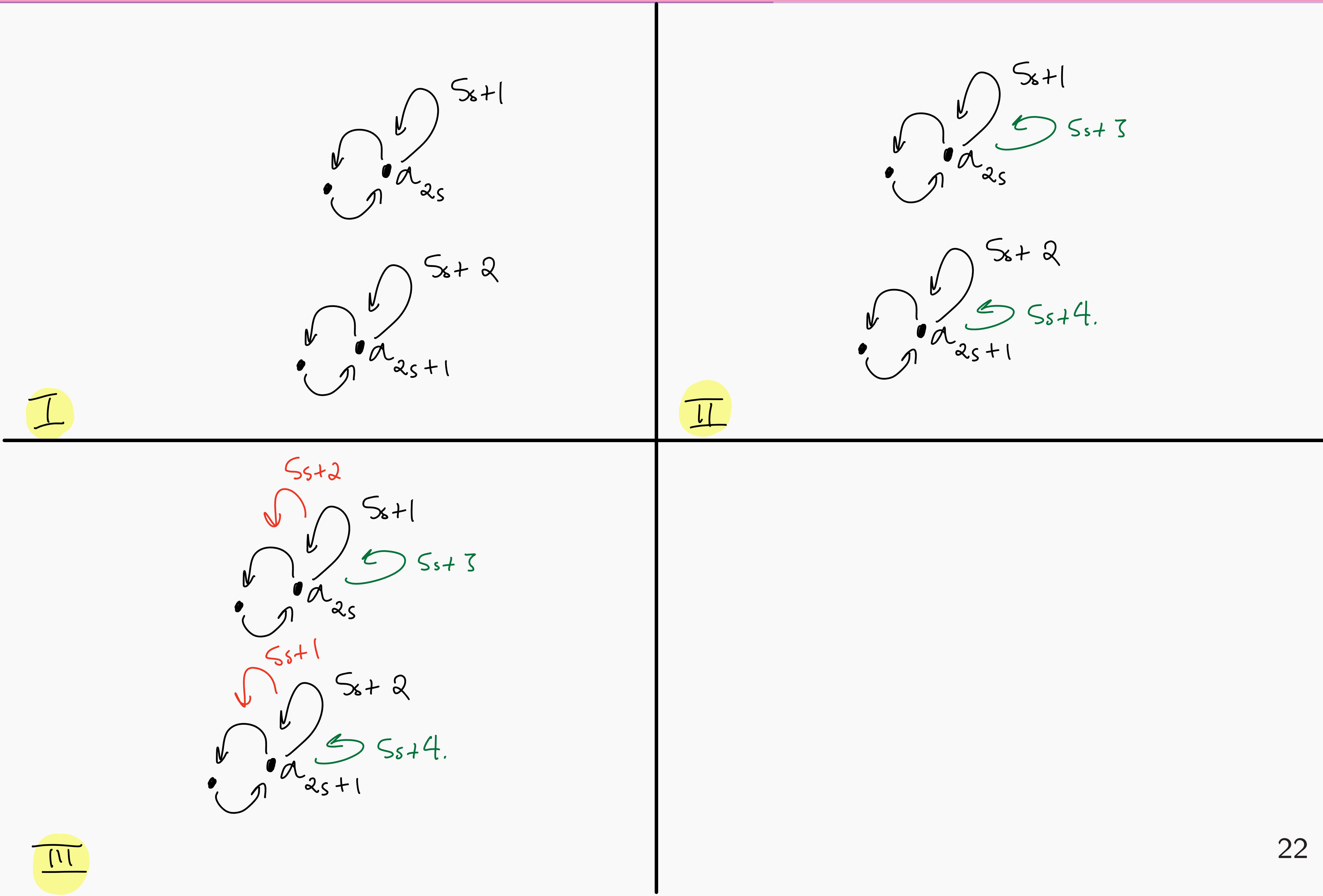
Definition

The root node a_{2s} in our graph $\mathcal{G}$ with its loops is the 2s**th connected component** or just the 2sth component of $\mathcal{G}$.

Configuration of loops in $\mathcal{G}$



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Let s be the current stage of the construction and let α be an N_e^p-strategy.

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2. Check if $\Phi_e^{\overline{D_p}}(x_\alpha)[s]\downarrow= 0$ and keep x_α out of A_p. If not, α takes no action at stage s. If so, α enumerates x_α into A_p and restrains $A_p \upharpoonright (\text{use}(\Phi_e^{\overline{D_p}}(x_\alpha)) + 1)$.

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1. If α is first eligible to act at stage s, it sets its parameter $n_\alpha = 0$. It looks for copies in $\mathcal{M}_e[s]$ of the $2n_\alpha$th and $(2n_\alpha + 1)$st components of $\mathcal{G}[s]$. It defines $f_\alpha[s]$ to be the empty map.

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2. If n_α is defined and $f_\alpha[s-1]$ is defined for all $m < n_\alpha$, α looks for copies of the $2n_\alpha$th and $(2n_\alpha + 1)$st components of $\mathcal{G}[s]$.

Basic strategies: S_e

3. If no copies of the $2n_\alpha$th and $(2n_\alpha + 1)$st components are found, α takes no additional action at stage s, retains the value of n_α, and sets $f_\alpha[s] = f_\alpha[s-1]$.

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3. If no copies of the $2n_\alpha$th and $(2n_\alpha + 1)$st components are found, α takes no additional action at stage s, retains the value of n_α, and sets $f_\alpha[s] = f_\alpha[s-1]$. If copies are found, α extends $f_\alpha[s-1]$ to $f_\alpha[s]$ by matching the components in $\mathcal{G}[s]$ to the copies found in $\mathcal{M}_e[s]$ and increments n_α by 1.

Basic strategies: T_i^p

Let $p \in P_0$. Our basic strategy to satisfy all T_i^p requirements to make $\mathcal{G}$ computably categorical relative to D_p is similar to our S_e-strategy. Let α be a T_i^p-strategy.

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For each n, we try to find copies of the $2n$th and $(2n+1)$st components of $\mathcal{G}$ in $\mathcal{M}_i^{D_p}$.

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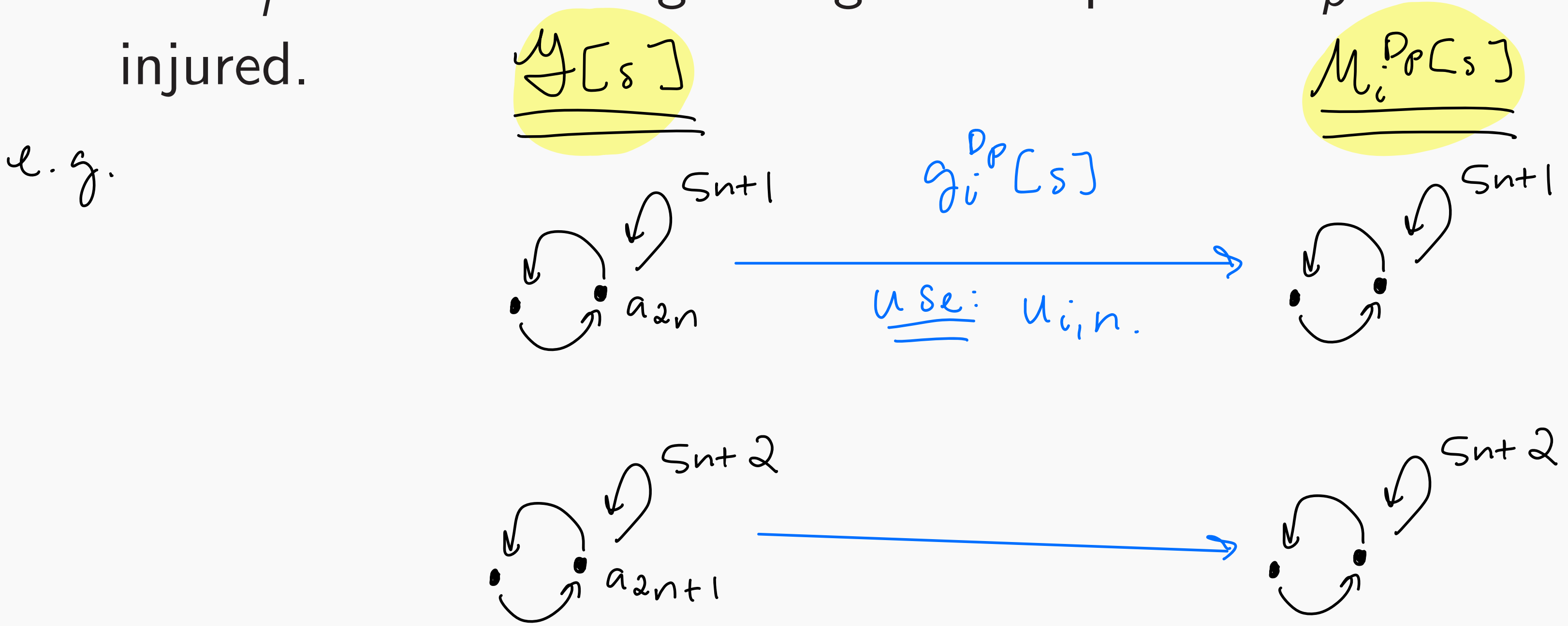
For each n, we try to find copies of the $2n$th and $(2n+1)$st components of $\mathcal{G}$ in $\mathcal{M}_i^{D_p}$. But now because D_p is a c.e. set, loops in $\mathcal{M}_i^{D_p}$ or embeddings using a finite part of D_p as an oracle be injured.



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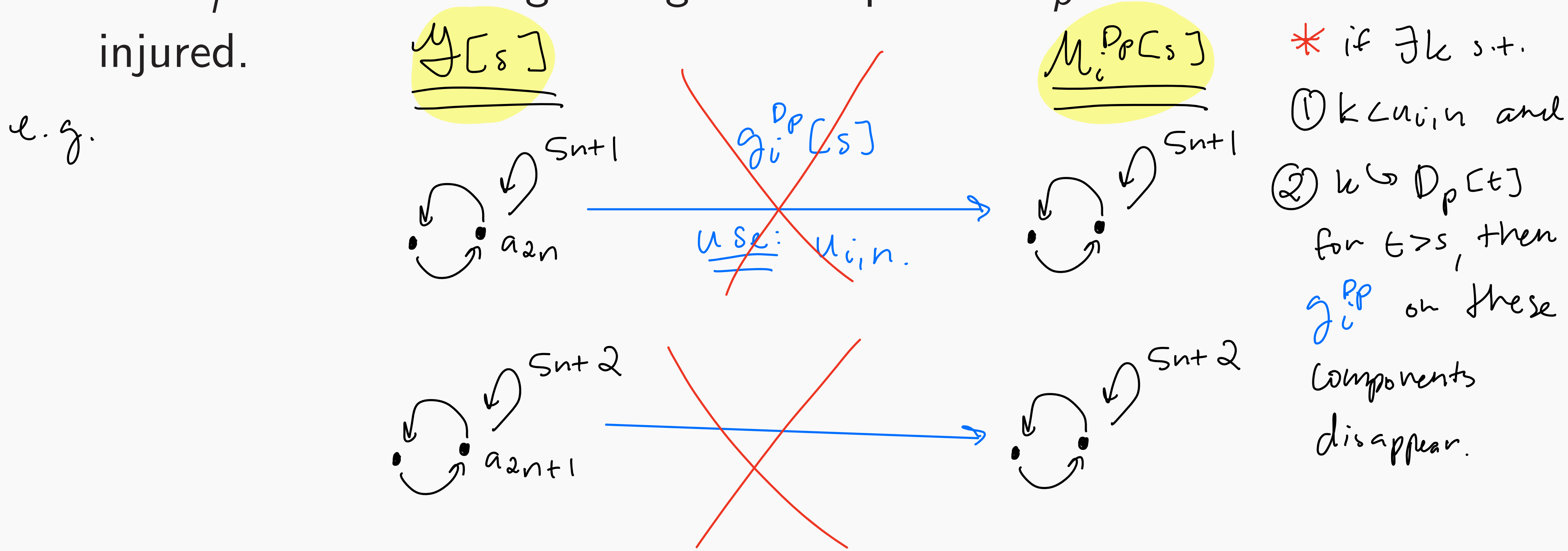

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If $D_p[t] \neq D_p[s]$, then α will update its parameter n_α accordingly depending on what type of injury occurred. Otherwise, it will proceed to try and match the $2n_\alpha$th and $(2n_\alpha + 1)$st components of $\mathcal{G}$ for the n_α parameter it had at the beginning of stage s.

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Finally, for $q \in P_1$, we do the following to satisfy all R_e^q requirements to make $\mathcal{G}$ not computably categorical relative to D_q.

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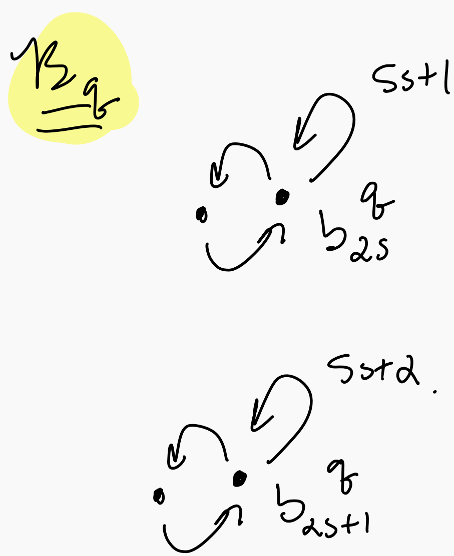

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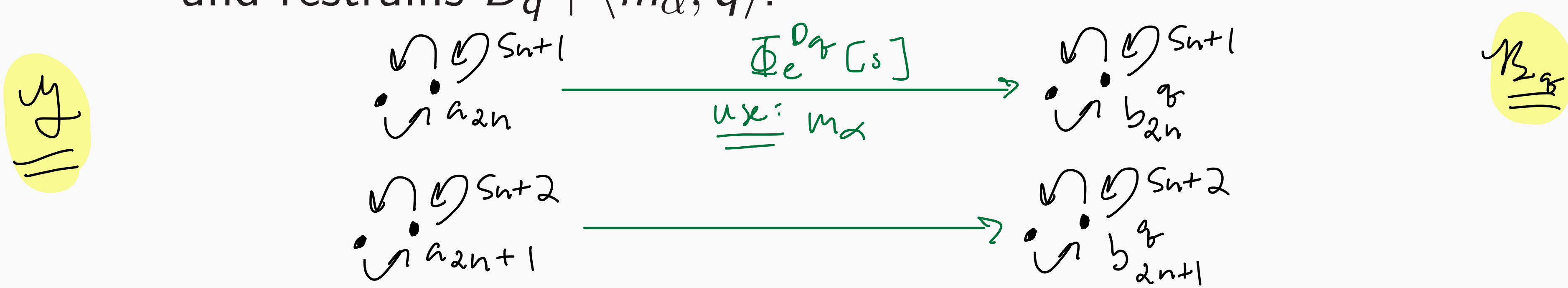

Basic strategies: R_e^q

3. α attaches a $(5n+3)$-loop to a_{2n} and b^q_{2n} and a $(5n+4)$-loop to a_{2n+1} and b^q_{2n+1}.

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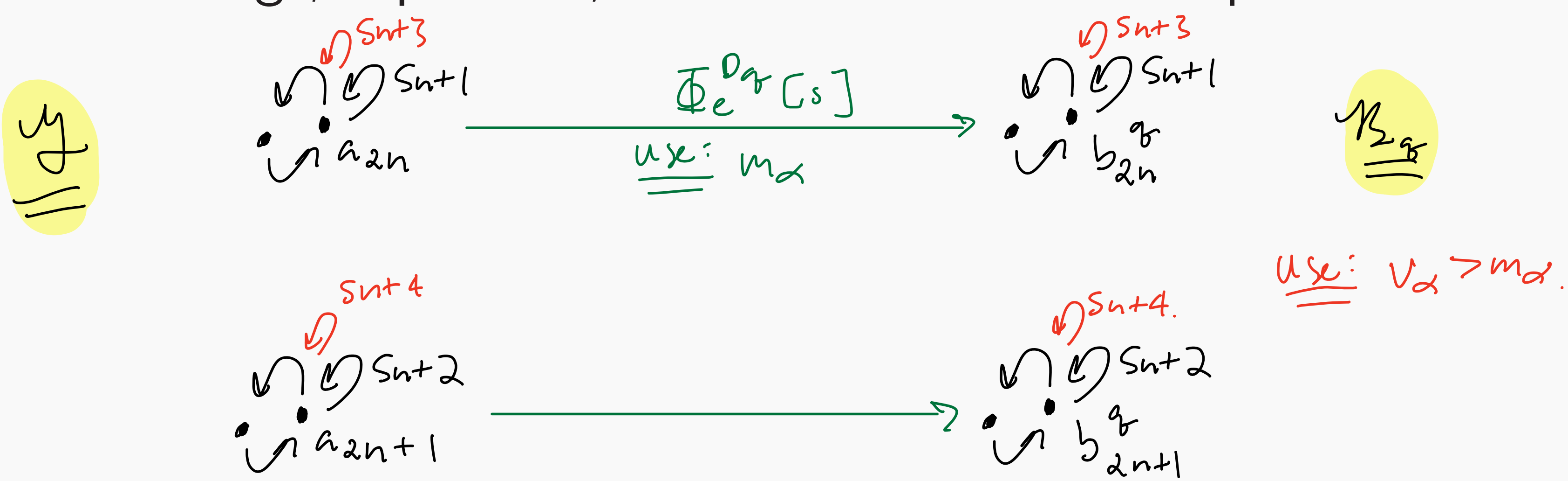
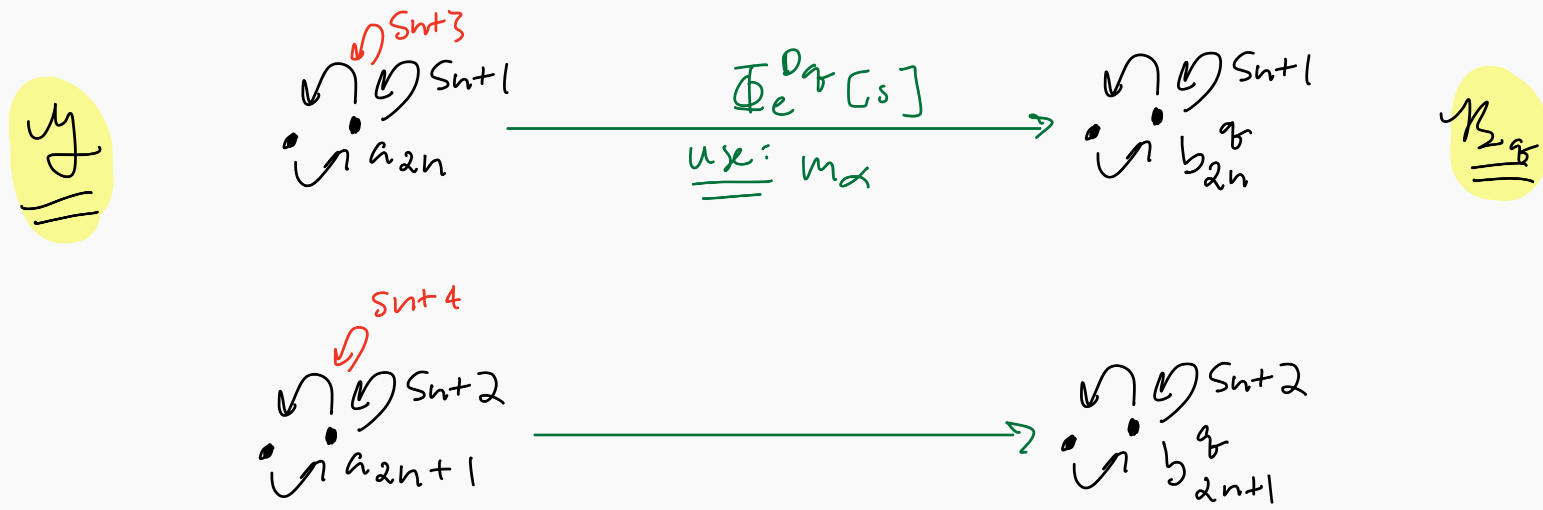
4. α now issues a challenge to all higher priority requirements which are S_e and T_i^p: they must now extend their embeddings, if possible, to include these new loops.



5. If all higher S_e and T_i^p requirements can meet this challenge and α becomes eligible to act again at a later stage, it enumerates v_α into A_q. This makes the $(5n+3)$- and $(5n+4)$-loops in $\mathcal{B}_q$ disappear.



Basic strategies: R_e^q

6. α reattaches a $(5n+3)$-loop to b^q_{2n+1} and a $(5n+4)$-loop to b^q_{2n}. It also attaches a $(5n+1)$-loop to a_{2n+1} and to b^q_{2n+1}, and a $(5n+2)$-loop to a_{2n} and to b^q_{2n}.

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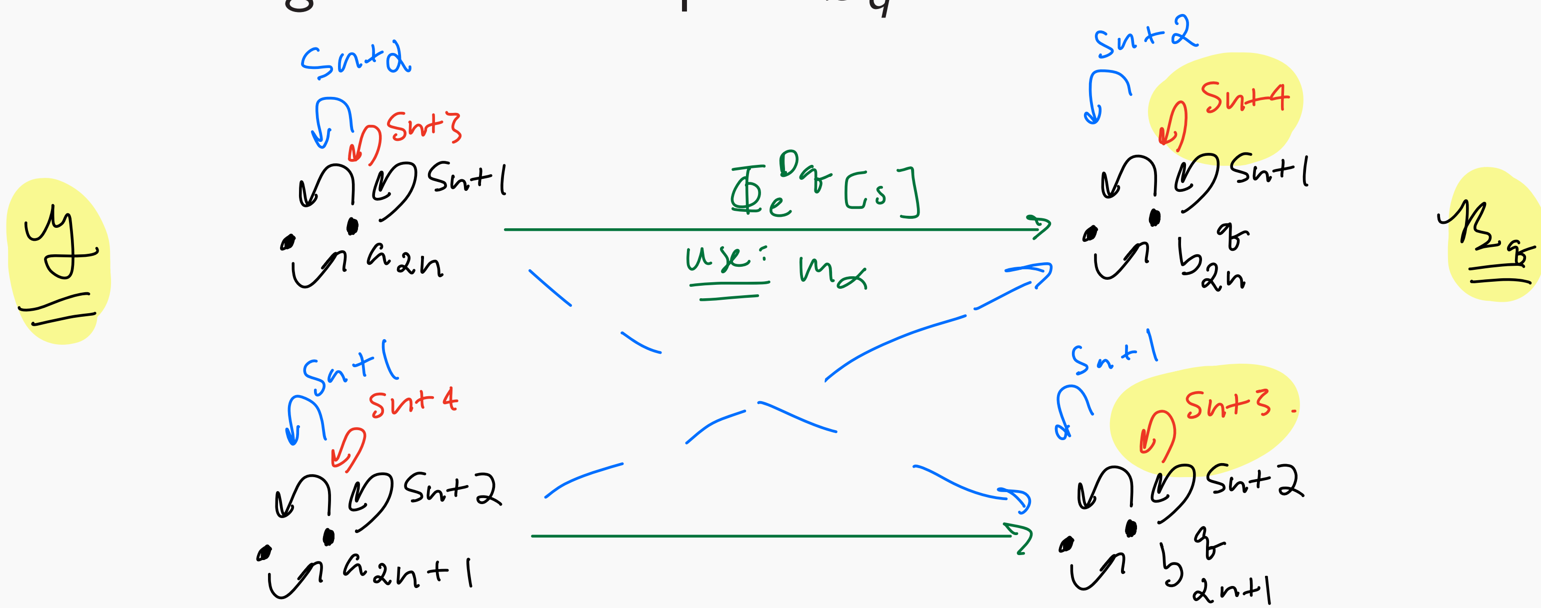
Our final configuration of loops in $\mathcal{B}_q$ is now:



Interactions between strategies

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Interaction 1

The R_e^q-strategy wants to diagonalize while the S_e and T_i^p-strategies want to build embeddings: this was resolved by having R_e^q "wait" for higher priority S_e and T_i^p requirements and the homogenizing part of step 6 in the R_e^q-strategy.

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Interaction 2

The N_e^p-strategy must enumerate numbers into A_p to achieve independence of degrees: this is resolved on a tree of strategies and by letting T_i^p check for any changes in D_p up to a finite part each stage.

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Interaction 3

An R_e^q-strategy β and a T_i^p-strategy α when $q < p$ in P and T_i^p is of higher priority than R_e^q: the T_i^p-strategy needs an additional step for when it is challenged to enumerate any uses associated to the $2n_\beta$th and $(2n_\beta + 1)$st components of $\mathcal{G}$ into A_p. This lets us lift uses for T_i^p so it can succeed.

Thanks

Thank you for your attention!

I'd be happy to answer any questions.

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