

Closed oriented 3-manifolds are equivalence classes of plane graphs *

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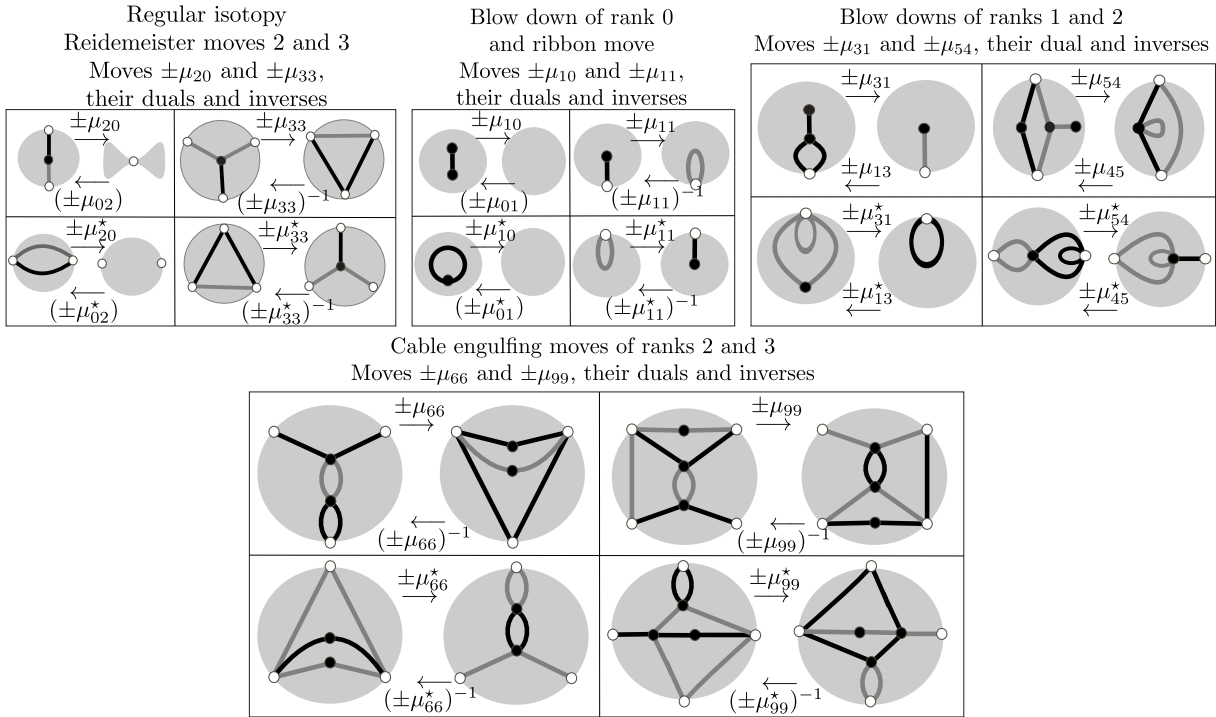
Abstract

A *blink* is a plane graph with an arbitrary bipartition of its edges. As a consequence of a recent result of Martelli, we show that the homeomorphisms classes of closed oriented 3-manifolds are in 1-1 correspondence with classes of blinks. Two blinks are equivalent if they are linked by a finite sequence of local moves, where each one appears in a concrete list of 64 moves: they organize in 8 types, each being essentially the same move on 8 simply related configurations. The size of the list can be substantially decreased at the cost of losing symmetry, just by keeping a very simple move, the *ribbon move* denoted μ_{11} (which is in principle redundant). Using μ_{11} makes all the moves coming from plane duality (the starred moves), except for μ_{20}^* , redundant.

1 Statement of the Theorem

This paper proves the following theorem:

(1.1) Theorem. *The classes homeomorphisms of closed oriented 3-manifolds are in 1-1 correspondence with the equivalence classes of blinks where two blinks are equivalent if they are linked by a finite sequence of the local moves where each term is one of the 64 moves (not necessary distinct) below*



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There are 64 local configurations divided into 32 pairs of left-right configurations, each one named a *coin*. A move replaces the left (right) coin of a pair by its right (left) coin. The complementary sub-blank in the exterior a coin is completely arbitrary; its intersection with the corresponding internal coin is the set of attachment vertices shown in the boundary of the disk (or pinched disk, in the case of ρ_2) where the coin lies. The number k of such attachment vertices satisfies $k \in \{0, 1, 2, 3, 4\}$.

2 A brief historical review: a result by Lickorish and consequences by Kirby, Fenn-Rourke, Kauffman and Martelli

A *knot* is an embedding of a circle, an \mathbb{S}^1 , into \mathbb{R}^3 or \mathbb{S}^3 . The *unknot* is a knot which is the boundary of a disk. A *link with k components* is an embedding of a disjoint union of k copies of \mathbb{S}^1 into \mathbb{R}^3 or \mathbb{S}^3 . In this way, a knot is a link with one component.

Knots and links can be presented by their *decorated general position projections* into a fixed plane \mathbb{R}^2 . *General position* means that in the image of the link there is no triple points and that at each neighborhood of each double is the transversal crossing of two segments of the link, named *strands*. *Decorated* means that we keep the information of which strand is the upper one, usually by removing a piece of the lower strand. In this paper we use another way to decorate the link projections: the images of the link components are thick black curves and the upper strands are indicated by a thinner white segment inside the thick black curve at the crossing.

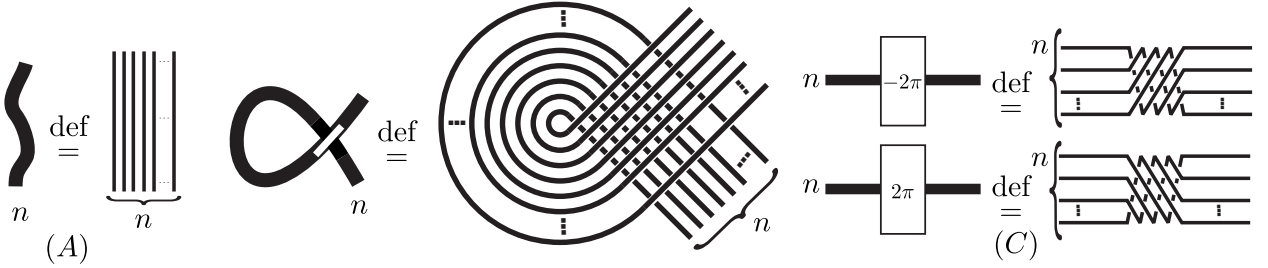


Figure 1: Notation for special disk neighborhoods of general position decorated link projections

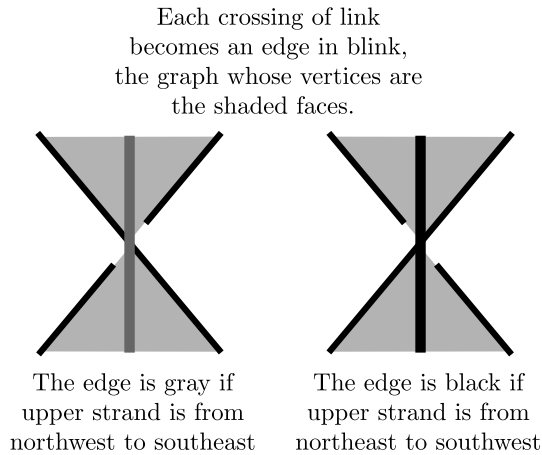


Figure 2: The projection of any link can be 2-face colorable into white and gray with the infinite face white so that each subcurve between two crossing have their incident faces receiving distinct colors. The above figure shows how to transform the projection into a blink (with thicker edges than the curves representing the link projection). The vertices of the blink are distinguished fixed points in the interior of the gray faces. The inverse procedure is clearly defined. Thus we have a 1-1 correspondence between general position decorated link projections and blinks.

In a groundbreaking work (1962), W.B.R. Lickorish, [5], proved that each closed orientable 3-manifold \mathbb{M}^3 can be encoded by a link in \mathbb{S}^3 where each one of its k components is endowed with an irreducible fraction (the framing) $\frac{\pm p}{q}$ where q could be 0, and in the case p must be 1 and the fraction becomes $\pm\infty$. To construct \mathbb{M}^3 from the framed link we act as follows: after removing from \mathbb{M}^3 an ϵ -neighborhood $(\mathbb{S}^1 \times \mathbb{D}^2)_i$ of the i -th link we are left with $\mathbb{M}^3 \setminus \bigcup_{i=1}^k (\mathbb{S}^1 \times \mathbb{D}^2)_i = \mathbb{S}^3 \setminus \bigcup_{i=1}^k (\mathbb{S}^1 \times \mathbb{D}^2)_i$. The fraction specifies, in the toroidal boundary inside \mathbb{S}^3 , the homology type $(\pm p, q)$ of the curve that is contractible in the solid torus inside \mathbb{M}^3 . For each component, we then identify the simple curve given by the homological base pair with the meridian of a canonical copy of a solid torus in \mathbb{R}^3 so as to completely specify the pasting of the solid torus closing the toroidal hole. Lickorish's breakthrough was to prove that any \mathbb{M}^3 has inside it a finite number k of disjoint solid tori so that $\mathbb{M}^3 \setminus \bigcup_{i=1}^k (\mathbb{S}^1 \times \mathbb{D}^2)_i = \mathbb{S}^3 \setminus \bigcup_{i=1}^k (\mathbb{S}^1 \times \mathbb{D}^2)_i$. Actually, this result had been proved 2 years before by A. H. Wallace [9] by using differential geometry. However it was the purely topological flavor of Lickorish's proof that spurs the subsequent developments.

In 1978 R. Kirby published his, to become famous, calculus of framed links, [4]. The gist of this paper is that two types of moves are enough to go from any framed link inducing a closed oriented 3-manifold to any other such link inducing the same manifold. One of the moves is absolutely local: creating or cancelling an arbitrary new component with frame in $\{\infty, -\infty\}$. The other type of move, the *band move* ([2]) (or *handle sliding*) is non-local and infinite in number.

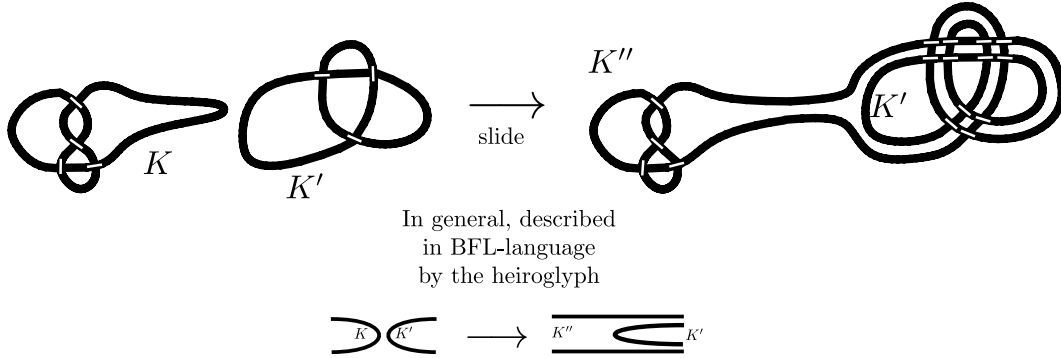


Figure 3: Kirby's handle slide move, also known as the band move. Given K and K' two distinct components of a link start by making a close parallel copy of K' in such a way that it has linking number 0 with its originator K' . Let K'' be the connected sum of K and the copy of K' . The connected sum is defined by a *band* which is a thin rectangle arbitrarily embedded into \mathbb{S}^3 , so as to miss the link. The short sides of the band are attached to K and to the copy of K' and are recoupled in the other way. Framings are modified in a judicious way. The situation loses no generality and becomes particularly simple if we have a blackboard framed link (shortly to be defined). More details in Kauffman's book, [2]. In blackboard framed language, this move is conveniently depicted via the heiroglyph shown above. See Section 12.3 of [3].

In 1979 R. Fenn and C. Rourke ([1]) show that Kirby's moves could be replaced by an infinite sequence of a single type of move (a *blow down move*) indexed by n , which we depict at the left side of Fig. 4. In a blow down move the number of components decreases by 1. This has been a very useful reformulation with many applications, including Martelli's calculus (soon to be treated) which uses it instead of the direct moves of Kirby.

In the beginning of the 1990's L. Kauffman presented ([2]) a completely planar diagrammatic way to deal with the calculus of Kirby and its reformulation by Fenn and Rourke. The basic idea comes from the fact that every 3-manifold is induced by surgery on a framed link which has *only finite integer framings*, which D. Rolfsen call *by honest surgery*, [8]. The proof of this result uses that it is possible to modify the framed link maintaining the induced 3-manifold so that every component becomes unknotted. A proof of this fact appears in Rolfsen's book. It also appears in page 137 of Kauffman-Lins monography, [3]. If a component is unknotted then it is simple to modify the link so that each component gets an integer framing, without disturb the integrality of the framing of other components. So, without loss of generality we may suppose that all the components have finite integers as framings. Kauffman's proceeds by adjusting each component by attaching to it a judicious number of curls so that the required framing of a component coincides with the algebraic sum of its self-crossings. By specifying that the link is *blackboard framed*, we no longer need the framings. In this work we only use links given by

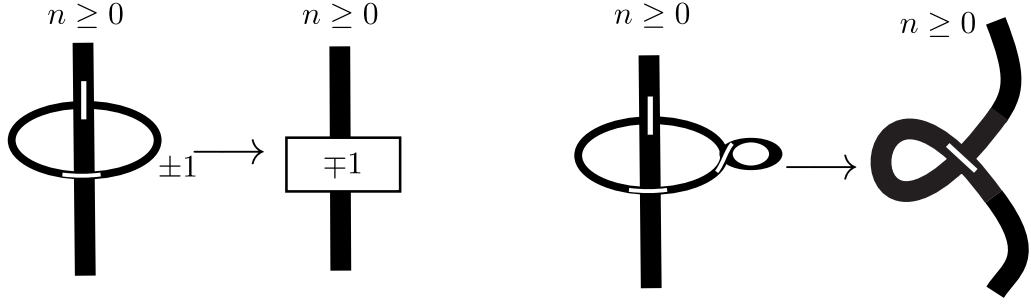


Figure 4: Fenn-Rourke infinite sequence of blown-down moves and their counterpart in Kauffman's blackboard framed links. These are infinite sequence of local moves. Cases $n = 0$ of these moves replace an isolated ± 1 -framed component or the unknot with one crossing by nothing. Martelli replaced the infinite sequence by the first three and two new simple moves A_3 and A_4 , described in Fig. 5.

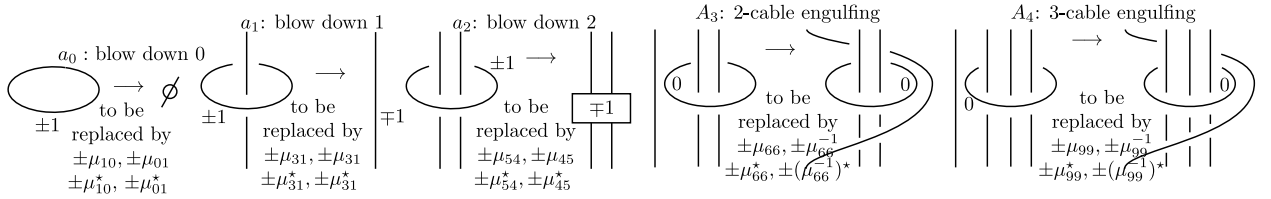


Figure 5: Martelli's calculus on fractional (or integer) framed links. He proves that by keeping only the blown down of ranks 0, 1 and 2 and replacing all the remaining infinite sequence by two new moves 2- and 3-cable engulfing (denoted by A_3 and A_4) a sufficient calculus for factorizing homeomorphisms between closed 3-dimensional 3-manifolds is achieved. Moves A_3 and A_4 do not translate into blink moves because their left sides are disconnected. What makes this work possible is the replacement of these non-connected configurations by equivalent moves a_3 and a_4 so that blink translations become available. See Fig. 6 where the diagrams for the moves appear -90° -rotated.

blackboard framed projections: they are rather close of blinks, which are purely graph theoretical plane graphs with an edge bipartition having no framing, see Fig. 2. The framings are internally reconstructible.

In an important recent paper B. Martelli [7] presented a local finite reformulation of the Fenn-Rourke version ([1]) of Kirby's calculus [4]. This calculus is presented in Fig. 5. It remains to be seen the consequences of Martelli's result for obtaining new 3-manifold invariants.

3 Objective of the work

Our objective here is to further reformulate Martelli's moves so as to obtain a calculus of blinks, denominated *blink-coin calculus*, which is an exact combinatorial counterpart for factorizing homeomorphisms of closed orientable 3-manifolds. This goal is desirable because it has the consequence that each 3-manifold become a subtle class of plane graphs. Our exposition is complete and elementary seeking to reach both audiences: topologists and combinatorialists. We feel that this result may be interesting for Combinatorics as well as to Topology and may enhance both areas. Plane graphs are one of the most studied objects in Combinatorics. Some of their properties could be used in 3-manifolds and vice-versa. As an example of an interesting question relating the two areas is this: which 3-manifolds correspond to the class of 3-connected monochromatic blinks? We have reasons to believe that the blink itself is a complete invariant for these manifolds. A catalogue of all the 242 blinks which are 3-connected, monochromatic and have up to 16 edges appear in [6].

4 Proof of the Theorem

(4.1) **Lemma.** *In the presence of $r_2^{\pm 1}$, moves $\pm a_3$ and $\pm A_3$ are equivalent and so are $\pm a_4$ and $\pm A_4$.*

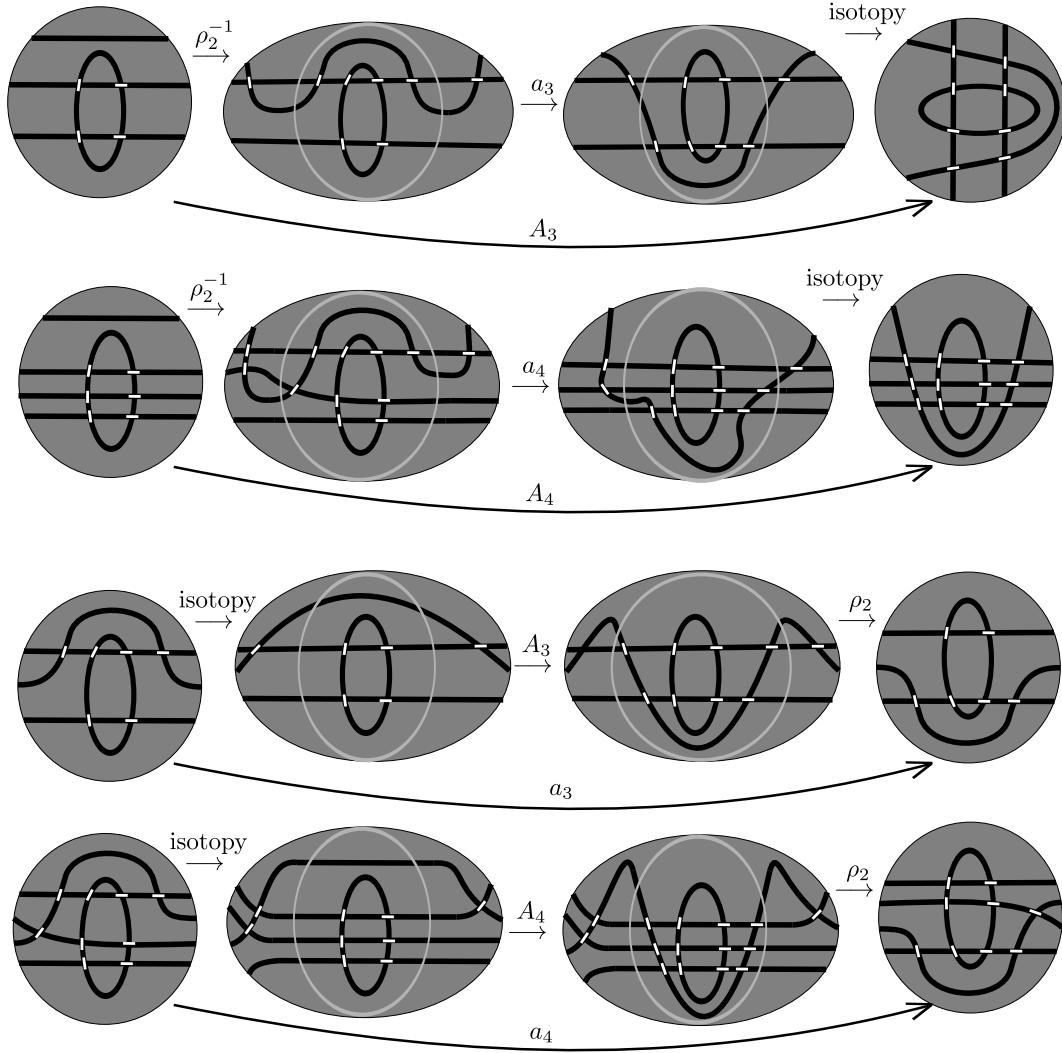


Figure 6: A proof that in the presence of $\pm r_2^{\pm 1}$, $a_3 \equiv A_3$ and $a_4 \equiv A_4$

Proof. We refer to Fig. 6. Its first line proves that $\pm a_3 \Rightarrow \pm A_3$. The second line proves that $\pm A_3 \Rightarrow \pm a_3$. The third line proves that $\pm a_4 \Rightarrow \pm A_4$. The last line proves that $\pm A_4 \Rightarrow \pm a_4$. \square

Proof. (of Theorem 1.1)

In Fig. 7 we draw all the moves for the revised Martelli's moves in a blackboard framing language and the respective blinks superimposed. The result follows by removing the superimposed moves leaving only the blink moves which are redraw up to isotopy in the lower part of the figure. \square

References

- [1] R. Fenn and C. Rourke. On Kirby's calculus of links. *Topology*, 18(1):1–15, 1979.
- [2] L.H. Kauffman. *Knots and physics*, volume 1. World Scientific Publishing Company, 1991.
- [3] L.H. Kauffman and S. Lins. Temperley-Lieb Recoupling Theory and Invariants of 3-manifolds. *Annals of Mathematical Studies, Princeton University Press*, 134:1–296, 1994.
- [4] R. Kirby. A calculus for framed links in S^3 . *Inventiones Mathematicae*, 45(1):35–56, 1978.

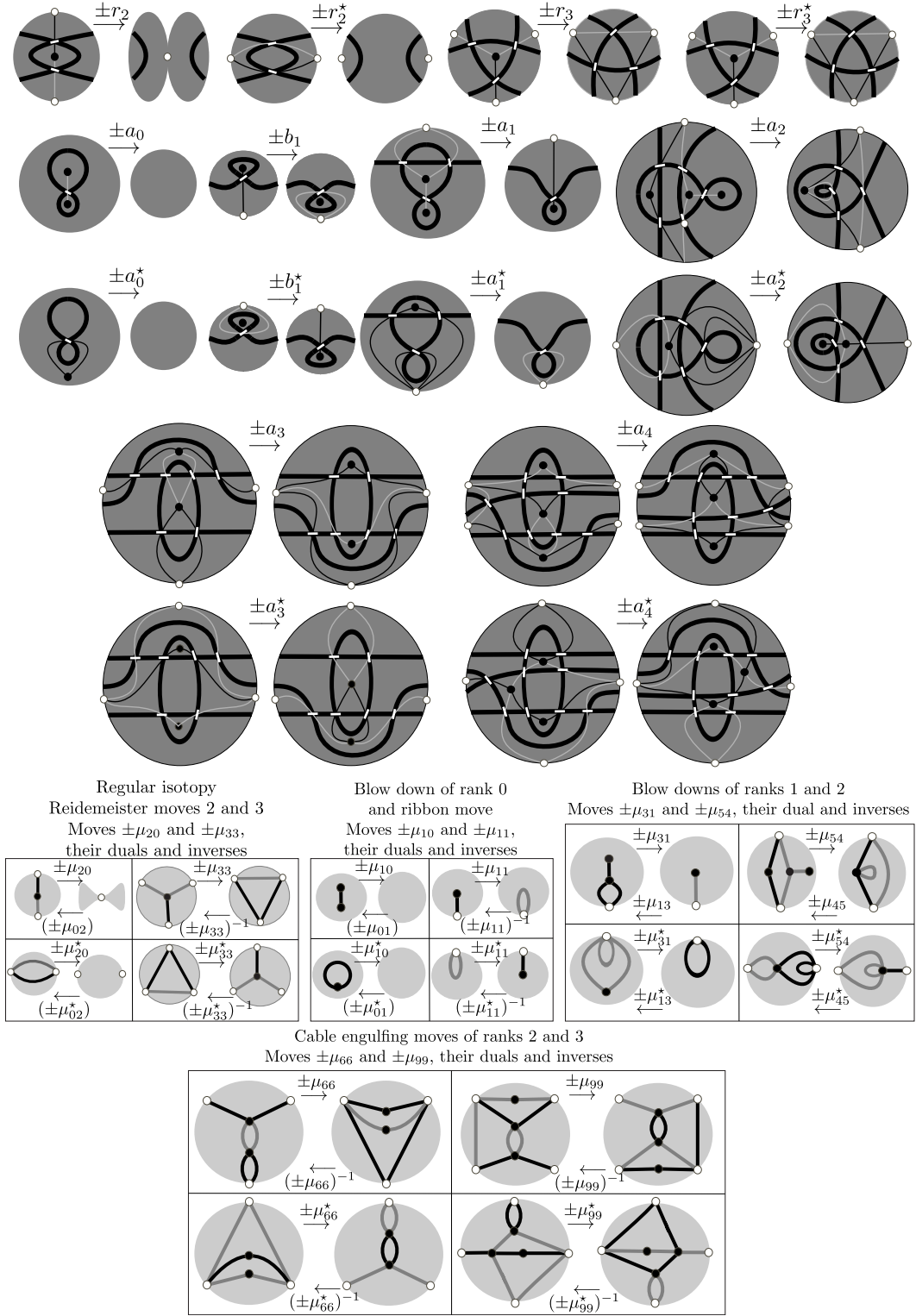


Figure 7: Blackboard framed version of Martelli's revised calculus with a_3 , a_4 replacing A_3 , A_4 . In the upper part of the figure, links & blinks are superimposed implying moves for the blink-coin calculus in the lower part of the figure, concluding the proof of the Theorem 1.1

- [5] W.B.R. Lickorish. A representation of orientable combinatorial 3-manifolds. *Annals of Mathematics*, 76(3):531–540, 1962.
- [6] L.D. Lins. Blink: a language to view, recognize, classify and manipulate 3D-spaces. *Arxiv preprint math/0702057*, 2007.
- [7] B. Martelli. A finite set of local moves for kirby calculus. *Journal of Knot Theory and Its Ramifications*, 21(14), 2012.
- [8] D. Rolfsen. *Knots and links*. American Mathematical Society, 2003.
- [9] A.H. Wallace. Modifications and cobounding manifolds. *Canad. J. Math*, 12:503–528, 1960.

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