Research Statement

1. Introduction and Background

Since Hill, Hopkins, and Ravenel's solution to the Kervaire invariant one problem [HHR16], there has been a tremendous amount of work in developing a deeper understanding of the algebra underlying equivariant stable homotopy theory. My work builds on several components of this program through the development and application of tools from equivariant category theory. These methods have previously led to developments in the study of equivariant symmetric monoidal structures and provided a solution to a conjecture of Blumberg and Hill.

In ongoing projects, I am using ideas and results from my prior work to form new connections with other fields of mathematics. One of my projects builds on ideas of Merling, who developed a genuine equivariant K theory for rings with action by a finite group G [Mer17]. Recently, I have extended this to an equivariant generalization of rings known as *Green functors*. This construction should have applications computations in K theory related to number theory and topology.

One can view K theory as a machine which produces topological data from categorical input. There is still more to understand about the ways that equivariant structures proceed through translations from categorical to topological information. In other ongoing projects, I am studying these phenomena in the contexts of stable homotopy theory and partition complexes. Both of these projects tie in to the theory of equivariant operads which index the various algebraic structures in equivariant stable homotopy theory.

1.1. Background.

Equivariant homotopy theory is the study of homotopical invariants, like cohomology, of spaces with an action by a fixed group G. Since not every space admits a non-trivial action by G, one should expect the class of spaces with G-action to systematically admit interesting structures not present for all spaces. This extra structure endows invariants of spaces with G-action with additional data and the study of the resulting algebraic structures is known as *equivariant algebra*. Equivariant algebra occupies an important place in algebraic topology and played a crucial role in Hill, Hopkins, and Ravenel's solution to the Kervaire invariant one problem [HHR16].

The most fundamental object in equivariant algebra is the *Mackey functor*. Roughly, a Mackey functor M for a finite group G consists of a collection of abelian groups $M(H)$ indexed on the subgroups $H \leq G$. These groups are connected by a system of additive operations which provide computational power. Mackey functors were originally defined by Dress to axiomatize various structures that arise in representation theory [Dre73]. They provide a useful framework for approaching problems in topology and algebra when a finite group is acting on objects of interest. The connection to equivariant homotopy theory comes from the following example.

Example 1.1. Let X be a space with action by a finite group G and let E be a *genuine G-spectrum*, i.e. a cohomology theory for spaces with G-action. For every n, there is a Mackey functor $E^n(X)$.

Mackey functors play a role in equivariant homotopy theory analogous to the role of abelian groups in ordinary algebraic topology. The use of Mackey functors in this way has its roots in work of Bredon, and was fully realized by a program of work due to Peter May and collaborators [Bre67, LMM81, May96]. Genuine equivariant cohomology theories are an alternative to the older Borel cohomology theories and have certain technical advantages. For example, the genuine theories satisfy a version of Poincaré duality for all compact G-CW complexes. By contrast, the Borel cohomology theory only satisfies Poincaré duality for G-CW complexes with free G-action. The duality of genuine theories was utilized, for example, in Manolescu's disproof of the triangulatation conjecture in high dimensions [Man16].

While Mackey functors are abelian groups in the equivariant setting, there are several generalizations of rings. A *Green functor* is (essentially) a Mackey functor R such that $R(H)$ is a ring for all $H \leq G$. A *Tambara functor* S is a commutative Green functor with additional multiplicative operations known as norm maps. Norm structures were first studied in connection to equivariant stable homotopy theory by Greenlees and May, and then more systematically by Hill, Hopkins, and Ravenel [GM97, HHR16]. The norm operations of a Tambara functor provide significant advantages when performing computations, and were a key ingredient in Hill, Hopkins, and Ravenel's seminal work on the Kervaire invariant one problem.

If E is a genuine G-ring spectrum (i.e. a multiplicative equivariant cohomology theory), and X is any G-space, then $E^0(X)$ is naturally a Tambara functor, and hence also a Green functor. More generally, Angeltveit and Bohmann have shown that the collection of Mackey functors $E^\star(X)$ fit into a graded Tambara functor [AB18]. Other examples of Green and Tambara functors arise naturally from group representation rings, Grothendieck–Witt rings, and Galois field extensions.

2. Prior and ongoing work

2.1. **Results of prior work.** The difference between Tambara and Green functors is rooted in categorical considerations. The category of Mackey functors has a symmetric monoidal product, called the box product, and the monoids are exactly the Green functors. To describe Tambara functors categorically, one considers an equivariant symmetric monoidal structure, in the sense of Hill and Hopkins, on the category of Mackey functors [HH16]. The Hoyer–Mazur theorem states that the category of Mackey functors admits such an equivariant symmetric monoidal structure, and Tambara functors are exactly the equivariant commutative monoids [Hoy14, Maz13, HM19].

In recent work, Blumberg and Hill study Tambara functors which are *bi-incomplete*, in the sense that they only have some of the usual additive and multiplicative operations [BH22]. These objects arise in the context of equivariant stable homotopy indexed on incomplete G-universes. Such G-universes provide an important technical groundwork for constructions in equivariant stable homotopy theory and arise naturally in geometric situations [BH21, Man16]. Other examples of bi-incomplete Tambara functors come from localizations in equivariant algebra and topology [HH14].

The data of a bi-incomplete Tambara functor is indexed by combinatorial objects known as a *transfer system*. Every bi-incomplete Tambara functor determines a pair of transfer systems: one for additive operations and one for multiplicative operations. Just as multiplication distributes over addition in a ring, the multiplicative operations of a bi-incomplete Tambara functor interact with the additive operations in interesting ways. Accordingly, only suitably compatible pairs of transfer systems can be used for indexing bi-incomplete Tambara functors. Unfortunately, checking whether two transfer systems are compatible is difficult from the definitions. While studying bi-incomplete Tambara functors I produced an efficient method for checking the necessary compatibility.

Theorem 2.1 (Theorem 4.10 of [Cha22])**.** *Compatibility of a pair of transfer systems is equivalent to an easily-checked combinatorial condition.*

Underlying every bi-incomplete Tambara functor is an *incomplete Mackey functor* – a Mackey functor missing some of its additive structure. Incomplete Mackey functors appear in topology as unstable equivariant homotopy groups [Lew92]. Bi-incomplete Tambara functors should be thought of as ring objects in incomplete Mackey functors and I recently made this analogy precise, answering a conjecture of Blumberg–Hill by proving a generalization of the Hoyer–Mazur theorem.

Theorem 2.2 (Proposition 6.7 and Theorem 8.4 of [Cha22])**.** *Any category of incomplete Mackey functors admits an equivariant symmetric monoidal structure whose equivariant monoids are the bi-incomplete Tambara functors.*

The models of equivariant symmetric monoidal structures used in Theorem 2.2 are the symmetric monoidal Mackey functors defined by Hill and Hopkins [HH16, HM19]. These can be thought of as Mackey functors in symmetric monoidal categories: a symmetric monoidal Mackey functor $\mathcal{C}$ consists of symmetric monoidal categories $\mathcal{C}(H)$ for every subgroup $H \leq G$. The categories $\mathcal{C}(H)$ are connected by strong monoidal functors that mirror data of ordinary Mackey functors. These functors are subject to a rather large amount of coherence data. In my thesis, I prove this coherence can be repackaged as a pseudofunctor which takes values in the 2-category of categories.

Theorem 2.3. *The symmetric monoidal Mackey functors of [HH16] are equivalent to product preserving pseudofunctors from the* Burnside category $\mathcal{A}^G$ *to the* 2*-category of categories.*

Packaging the coherence this way allows for efficient construction of examples, such as that of Theorem 2.2. A more subtle advantage of Theorem 2.3 is that our pseudofunctors are landing in the 2-category of categories, instead of symmetric monoidal categories. Valuing our pseudofunctors in a less structured 2-category allows us to generalize Tambara functors to this context.

Definition 2.4. There is a category $\mathcal{P}^G$ such that Tambara functors are exactly product preserving functors from $\mathcal{P}^G$ into the category of sets. We define a symmetric monoidal Tambara functor to be a pseudofunctor from $\mathcal{P}^G$ to the 2-category of categories.

Proposition 2.5. *The symmetric monoidal (incomplete) Mackey functors of Theorem 2.2 extend to symmetric monoidal (bi-incomplete) Tambara functors.*

Theorem 2.3 is connected to the study of genuine G-spectra by the following theorem of Guillou and May.

Theorem 2.6 ([GM11], also see [Bar17])**.** *The category of genuine G-spectra is Quillen equivalent to the category of "spectrally enriched functor" from $\mathcal{A}^G$ to the category of ordinary spectra. Such functors are called spectral Mackey functors.*

To produce a spectral Mackey functor from a symmetric monoidal Mackey functor, it suffices to have a construction which produces a spectrum for each of the constituent symmetric monoidal categories; this is precisely the job of Segal's K theory machine [Seg74, EM06].

Proposition 2.7 (c.f. [BO15, MM19])**.** *Every symmetric monoidal Mackey functor $\mathcal{C}$ determines a genuine G-spectrum $\underline{K}(\mathcal{C})$ called its* algebraic K theory*. A similar construction can be made when replacing symmetric monoidal categories with Waldhausen categories.*

Goal 2.8. Study the multiplicative structure of $\underline{K}(\mathcal{C})$.

Multiplicative structures on G-spectra are more subtle than ordinary spectra. In [GM11], the authors remark it is not known when a spectral Mackey functor is a commutative G-ring spectrum. This poses an obstacle to computational methods in equivariant stable homotopy theory. The obvious guess is that one should expect commutative ring G-spectra to be modeled by spectral Mackey functors which are commutative monoids with respect to the Day convolution product of functors. This guess, however, seems to be incorrect because we can construct counterexamples using Proposition 2.7. To show these counterexamples are not ring spectra, we compute that the zeroth homotopy group is *not* a Tambara functor.

These counterexamples suggest that what is missing from our initial guess is the existence of norm data in our spectral Mackey functors. At the categorical level, an approach to keeping track of norms is through the categorical Tambara functors of Definition 2.4. I conjecture that if $\mathcal{C}$ is a categorical Tambara functor then its K theory is a ring G-spectrum. From a theoretical standpoint, one can view this conjecture as a form of the Hoyer–Mazur theorem that identifies equivariant commutative monoids in G-spectra with "spectral Tambara functors." As a starting point for this project, I am working to make the definition of spectral Tambara functors precise.

2.2. Algebraic K Theory of Green functors.

In joint work with Maxine Calle and Andres Mejia we are studying a new construction which assigns a genuine G-spectrum to each Green functor which I call *Green functor K theory.* The definition of Green functor K theory proceeds by assigning a Mackey functor of Waldhausen categories to each Green functor, and taking its algebraic K theory as in Proposition 2.7 to produce a genuine G-spectrum. The constituent Waldhausen categories of this Mackey functor are categories of finitely generated projective modules over the Green functor S, and other Green functors derived from S.

Examples of Green functors come from rings with G action. Every ring S with action by G determines a *fixed point Green functor* $FP(S)$ defined by $FP(S)(H) = S^H$. Merling has defined a separate equivariant K theory for rings with G-action and our constructions are often the same.

Theorem 2.9 ([CCM], in preparation)**.** *Let S be a ring with action by a finite group G. If $|G|$ is invertible in S, then there is an equivalence $K(FP(S)) \cong K_M(S)$, where K_M is Merling's K theory.*

The proof of Theorem 2.9 proceeds by showing there is actually an equivalence between categories of finitely generated projective modules over S and $FP(S)$. When the order of G is not invertible, the difference between these constructions can be understood in terms of the modular representation theory of the group G. We also conjecture the following splitting theorem.

Conjecture 2.10. *For any G-Green functor S, there is a splitting of G-spectra:*

$$K(S)^G \cong \bigvee_{(H)} K(S_H)$$

where the wedge runs over representatives of the conjugacy classes of subgroups of G, and S_H is a particular quotient of the ring $S(G/H)$.

This splitting mirrors a similar result in equivariant A theory [MM19, BDa17]. We have been able to prove the analogous result when K theory is replaced with G theory. The G theory splitting generalizes work of Greenlees, and its proof leverages a filtration of the category of Mackey functors due to Lewis [Gre92, Lew80]. The most immediate goal for this project is to adapt this argument to prove Conjecture 2.10. Other goals of this project are outlined below.

Goal 2.11. Perform computations of Green functor K groups.

Computations of K groups are famously difficult, but in some examples it seems possible to perform computations for K theory of Green functors by leveraging existing knowledge. A first step is to consider the fixed point Green functors of finite fields with Galois actions. As observed by Merling, and in view of Theorem 2.9, the K theory of these Green functors is related to the Quillen–Lichtenbaum conjecture. Computations for these Green functors are particularly accessible since Quillen computed the algebraic K theory of finite fields [Qui72]. Additionally, modules over these Green functors are particularly simple since, by the observation of Nakaoka [Nak12], these fixed points Green functors are "Tambara fields." Beyond finite fields, we hope to leverage the splitting of Conjecture 2.10 to perform computations from existing knowledge of the K theory of rings. These computations would be furthered significantly by successful work on Goal 2.8.

Goal 2.12. Interpret low dimensional K-groups via algebra and topology.

Low dimensional K groups are particularly interesting because they can often be understood in simpler terms than as homotopy groups of a space. It would be illuminating to make sense of these in the equivariant setting to develop, for instance, a more complete picture of matrices and determinants for Green functors. These low dimensional groups are also related to topology via constructions such as Wall's finiteness obstruction, Whitehead torsion, and the Waldhausen linearization map. Understanding how Green functor K theory fits into the equivariant versions of these stories would provide a topological interpretation of the constructions.

Goal 2.13. Construct an equivariant Dennis trace map.

Classically, the K theory and topological Hochschild homology of rings are related by the Dennis trace map, which has been utilized to great effect in computations of algebraic K theory [DGM13]. Topological Hochschild homology for Green functors, and G-ring spectra, has already been studied in the literature [BGHL19, ABG+18, AGH+22a, AGH+22b]. It would be useful for our theoretical understanding to have a Dennis trace in this setting and existing computations of THH could be leveraged to shed light on our own. We expect the construction to proceed essentially the same as it does classically.

2.3. **Partition complexes and equivariant operads.** Let $\underline{n}$ be a set with n elements and let $\mathcal{P}(n)$ denote the collection of non-trivial partitions of $\underline{n}$. Since $\mathcal{P}(n)$ is a poset, we can form a simplicial complex $|\mathcal{P}(n)|$ whose vertices are the elements of $\mathcal{P}(n)$ and whose higher dimensional simplices correspond to chains in the poset. This simplicial complex is the classifying space of the category underlying $\mathcal{P}(n)$. The space $|\mathcal{P}(n)|$ is homeomorphic to the space of trees whose leaves are labeled by the set $\underline{n}$. This space has been studied extensively and has connections to Lie algebras, operad theory, and Goodwillie calculus [Rob04, AD01, HM21, Fre04].

In ongoing joint work with Bergner, Bonventre, Calle, and Sarazola we are studying the properties of partition complexes that arise by replacing the set $\underline{n}$ by a finite G-set. We begin by reframing a partition of $\underline{n}$ as a surjective map $\underline{n} \to \underline{k}$ where the the components of a partition correspond to the preimages of points in $\underline{k}$. We define an equivariant partition of a G-set A to be either a surjective map $A \twoheadrightarrow \underline{k}$, or a surjective, equivariant map $A \twoheadrightarrow B$ where B is another G-set.

Our equivariant partitions lead to two different simplicial complexes which we denote $|\mathcal{P}(A)|$ and $|\mathcal{P}^G(A)|$, respectively. The complex $|\mathcal{P}(A)|$ has an action by G and $|\mathcal{P}^G(A)|$ is recovered as the fixed points of this action.

Theorem 2.14 ([BBC+], in preparation)**.** *For any subgroup $H \leq G$, there is a homotopy equivalence between $|\mathcal{P}(A)|^H$, the H-fixed points of $|\mathcal{P}(A)|$, and $|\mathcal{P}^H(A)|$.*

Since $|\mathcal{P}^H(A)|$ is the classifying space of a category, we are able to access information about the fixed points of $|\mathcal{P}(A)|$ algebraically. In particular, if $G = \Sigma_n$ and $A = \underline{n}$, we are able to provide new proofs of some results of [AB21] on the fixed points of the symmetric action on $|\mathcal{P}(n)|$. These fixed points are related to computations of Bredon cohomology, see [ADL16] for a full discussion.

Leveraging an understanding of how equivariant structures proceed through the classifying space construction, we extend work of Heuts and Moerdijk to our setting [HM21].

Theorem 2.15 ([BBC+], in preparation)**.** *There is a G-homotopy initial map from $P(A)$ to the space of equivariant trees labeled by A. This map is, in particular, a G-homotopy equivalence.*

In the course of proving Theorem 2.15 we develop general tools for equivariant homotopy theory. Among other things, we prove an equivariant generalization of Quillen's Theorem A. Additionally, we offer a different perspective on related work, providing new proofs of some results of [AB21].

Goal 2.16. Study equivariant operads using Theorem 2.15 and Theorem 2.1.

Non-equivariantly, the relationship between partition complexes and trees provides a connection to operads via the Boardman–Vogt W-construction [BV73]. Equivariantly, we expect there to be a similar story relating our partition complexes and the genuine equivariant operads of Bonventre and Pereira [BP21]. The homotopy theory of these operads is more subtle than it is in the non-equivariant setting, and is related to the poset of transfer systems I studied in Theorem 2.1.

Important examples of equivariant operads are the linear isometries operads which parameterize multiplicative structures on G-equivariant ring spectra. Rubin has in some cases classified the kinds of transfer systems that can arise from the related equivariant Steiner operads. A classification of those determined by linear isometries operads remains unknown [Rub21]. The transfer systems of linear isometries and Steiner operads are naturally compatible in the sense of [BH22]. Reframing this compatibility in combinatorial terms as in Theorem 2.1 could provide an avenue for classifying the linear isometries operads via their compatibility with the Steiner operads. Such a classification would improve our understanding of multiplicative equivariant structures.

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