## Structures on Forms of K-Theory

The Harvard community has made this article openly available. **Please share** how this access benefits you. Your story matters

<table>
<thead>
<tr>
<th>Citation</th>
<th>Sia, Charmaine Jia Min. 2015. Structures on Forms of K-Theory. Doctoral dissertation, Harvard University, Graduate School of Arts &amp; Sciences.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citable link</td>
<td><a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:17467390">http://nrs.harvard.edu/urn-3:HUL.InstRepos:17467390</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA">http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA</a></td>
</tr>
</tbody>
</table>
Structures on Forms of $K$-Theory

A dissertation presented

by

Charmaine Jia Min Sia

to

The Department of Mathematics

in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Mathematics

Harvard University
Cambridge, Massachusetts

April 2015
Structures on Forms of $K$-Theory

Abstract

In the early 1970s, Morava studied forms of topological $K$-theory and observed that they have interesting number theoretic connections. Until very recently, forms of $K$-theory have not been studied in greater depth and integrated into the modern theory of topological modular forms. In this dissertation, some expected structured ring spectra and locality results are established on forms of $K$-theory. Forms of algebraic structures are usually classified by Galois cohomology. Based on the structured ring spectra and locality results established, a criterion is given for distinguishing homotopy equivalence classes of forms of $K$-theory via a computation in the second homotopy group of the spectrum.
## Contents

- **Acknowledgements** v  

1 Introduction 1  
  - 1.1 Historical Background ........................................ 1  
  - 1.2 Modern Framework .............................................. 5  
  - 1.3 Statement of the Main Results .................................. 9  

2 Main Results 11  
  - 2.1 Preliminaries .................................................... 11  
  - 2.2 Proofs of the Main Results ..................................... 15  

3 Future Directions 20  

References 21
Acknowledgements

First and foremost, I would like to thank my advisor, Michael Hopkins, for his constant support, understanding, and patience. I would also like to thank Mark Behrens and Mike Hill for their generosity with ideas for further directions. Thanks go also to the algebraic topology group at Harvard and MIT, from whom I always learnt something new, and my fellow graduate students and other members of the Department of Mathematics, who brightened the department. Last but not least, I would like to thank my family for supporting me in pursuing a doctorate, Chao for his love and support и Мишу, который всегда поддерживал меня.
1 Introduction

1.1 Historical Background

A principal open problem in algebraic topology is to uncover patterns in and compute the stable homotopy groups of spheres. The contemporary approach of chromatic homotopy theory seeks to capture periodic phenomena in layers enumerated by a non-negative integer \( n \) known as the height, analogous to the constituent frequencies of light. Complex \( K \)-theory is the exemplar of a height one cohomology theory, or equivalently, its representing object, a spectrum. Its \( p \)-adic completion \( K_p \) lies at the bottom of a family of spectra known as Morava \( E \)-theory \( E_n \): \( K_p \) is a first Morava \( E \)-theory \( E_1 \). Morava \( E \)-theory \( E_n \) is central to the study of the \( n \)th monochromatic layer, and the fundamental work of Goerss, Hopkins, and Miller \cite{GHM} establishes it as a highly structured commutative, or \( E_\infty \)-, ring spectrum, which enables various sophisticated constructions.

In 1973, Morava, motivated by classical questions about integrality properties of characteristic classes of smooth manifolds, studied forms of \( p \)-complete \( K \)-theory cohomology \( K^*_p(\cdot) \) \cite{Morava}. Generally speaking, a form of an algebraic structure over a base is an object of the same type such that the two objects become isomorphic after extension of their common base:

**Definition 1.1.** Given a category \( \mathcal{C} \) with pullbacks, an object \( S \) in \( \mathcal{C} \), and an object \( S' \rightarrow S \) in the overcategory \( \mathcal{C}_{/S} \), an \( S'/S \)-form of an object \( X \rightarrow S \) in \( \mathcal{C}_{/S} \) is another object \( Y \rightarrow S \) in \( \mathcal{C}_{/S} \) such that the pullbacks \( X \times_S S' \rightarrow S' \) and \( Y \times_S S' \rightarrow S' \) are isomorphic.

The analogous definition with pushouts instead of pullbacks can be made in the opposite category \( \mathcal{C}^{\text{op}} \). We shall work in the latter context.
The concept of forms occurs in many algebraic areas of mathematics as it is related to descent theory.

**Definition 1.2.** A $W(\overline{F}_p)/\mathbb{Z}_p$-form of $p$-complete $K$-theory cohomology $K^*_p(\cdot)$ is a multiplicative cohomology theory $R^*(\cdot)$ taking values in the category of $\mathbb{Z}_p$-modules, with the property that

$$K^*_p(\cdot) \otimes_{\mathbb{Z}_p} W(\overline{F}_p) \cong R^*(\cdot) \otimes_{\mathbb{Z}_p} W(\overline{F}_p)$$

as multiplicative cohomology theories (although not canonically).

Here $W(\overline{F}_p)$ is the ring of $p$-typical Witt vectors of $\overline{F}_p$, obtained by adjoining to $\mathbb{Z}_p$ all primitive $m^{th}$ roots of unity, where $m$ is coprime to $p$, and taking its $p$-completion. Recall that $\mathbb{Z}_p = W(F_p)$. Morava showed:

**Theorem 1.3 (Morava [8]).** There is a bijection

$$\{\text{isomorphism classes of } W(\overline{F}_p)/\mathbb{Z}_p\text{-forms of } K^*_p(\cdot)\} \xrightarrow{\cong} \mathbb{Z}_p^\times.$$

He observed that forms of $K$-theory have interesting number theoretic connections, for example to the Ramanujan tau function or the quartic residue character.

**Example 1.4 (Morava [8]).** The Ramanujan tau function is the multiplicative function $\tau : \mathbb{N} \rightarrow \mathbb{Z}$ defined by the generating function

$$\sum_{n \geq 1} \tau(n)q^n = q \prod_{n \geq 1} (1 - q^n)^{24} = \Delta(z),$$

where $\Delta(z)$ is the discriminant modular form and $q = \exp(2\pi iz)$, $\Im z > 0$. 

2
There is a $W(\mathbb{F}_{11})/\mathbb{Z}_{11}$-form $R^*(-)$ of $K^*_1(-)$ whose associated topological index

$$t\text{-ind } R^* : MU_* \to \mathbb{Z} \subset \mathbb{Z}_{(11)}$$

satisfies

$$t\text{-ind } R^*(\mathbb{C}P(n-1)) = \tau(n) \text{ and } t\text{-ind } R^*(M \times N) = t\text{-ind } R^*(M) \cdot t\text{-ind } R^*(N).$$

Nowadays, there is a theory that makes Example 1.4 conceivable, if no less surprising: the theory of topological modular forms, which is a universal object mapping to elliptic cohomology theories—even periodic multiplicative cohomology theories $E^*(-)$ whose formal group law is isomorphic to the formal group law of a elliptic curve over $E^0(*)$—and whose coefficient ring is closely related to the classical ring of modular forms. The theory of topological modular forms is intricately connected to the height two layer in chromatic homotopy theory. From a modern perspective, the $W(\mathbb{F}_{11})/\mathbb{Z}_{11}$-form $R^*(-)$ of $K^*_1(-)$ in Example 1.4 is an elliptic cohomology theory for the modular group $\Gamma_0(11)$ of level 11.

Morava’s results were proven when $E_\infty$-ring spectra, which enable a strengthening of his results, were in their infancy, and before the advent of elliptic cohomology. Forms of $K$-theory were not studied in greater depth until 2009, when they began to be studied by Behrens and Lawson [2], Lawson and Naumann [6], and Hill and Lawson [4] in connection with the modern theories of topological modular and automorphic forms.

In the present dissertation, I study forms of $K$-theory in the contemporary framework of structured ring spectra (in a suitable Bousfield localized category)—specifically forms of the $p$-adically complete $K$-theory spectrum $K_p$—in an attempt to bring new
insights to the chromatic picture.
1.2 Modern Framework

In the years since Morava proved his results, there have been developments in homotopy theory that enable one to formulate a strengthening of Morava’s results. In this subsection, we briefly recall three key components of this framework: \( E_\infty \)-ring spectra, Morava \( K \)-theory \( K(n) \), and a power operation \( \psi \) for \( K(1) \)-local \( E_\infty \)-ring spectra which we shall subsequently require.

\( E_\infty \)-ring spectra can be motivated as follows. Recall that ring spectra are ring objects when regarded as objects in the homotopy category of spectra. For sophisticated applications such as the construction of homotopy fixed points under a group action or quotient spectra, however, one does not wish to forget all information when passing to the homotopy category of spectra, nor is it feasible to restrict consideration to ring objects in the original category. A compromise suitable for describing the multiplicative structure on \( K \)-theory and other spectra of interest is to not only require the spectrum to be a ring spectrum, but simultaneously remember the homotopies that make the relevant diagrams commute and higher homotopies between these homotopies; these are known as coherence conditions. This notion is precisely defined using the notion of an algebra over the \( E_\infty \)-operad \[7\], and spectra with this data are called \( E_\infty \)-ring spectra.

It is common to study the category of ring spectra via its fields, namely the ring spectra \( E \) such that every module spectrum over \( E \) is free, that is, it is a wedge of suspensions of \( E \). The fields in the category of ring spectra form a family known as Morava \( K \)-theory \( K(n) \), which correspond to a height \( n \) cohomology theory for each non-negative integer \( n \) and a fixed prime \( p \). Given \( K(n) \), we can consider the operation of Bousfield localization with respect to it. It turns out that \( K(n) \)-localization has several nice properties: for instance, it does not affect the \( n^{th} \) monochromatic layer,
and results about the $K(n)$-local category for different $n$ and $p$ can be combined to give information about the stable homotopy category. The first Morava $K$-theory $K(1)$ is closely related to the $p$-complete $K$-theory spectrum $K_p$ as follows. The group $\mathbb{Z}_p^\times$ of $p$-adic units acts on $K_p$ via the Adams operations $\psi^\lambda$, $\lambda \in \mathbb{Z}_p^\times$. For $p \geq 3$, the maximal finite subgroup $\mu$ of $\mathbb{Z}_p^\times$ is the group of $(p-1)$th roots of unity, and $K(1)$ can be obtained as $K_p^{Ad}/p$, where $K_p^{Ad}$ is the Adams summand of $K_p$, its homotopy fixed points by the action of $\mu$. In general, $K_p/p$ is a wedge of $p-1$ copies of suspensions of $K(1)$.

A $K(1)$-local $E_\infty$-ring spectrum $R$ possesses operations

$$\theta, \psi : \pi_0(R) \to \pi_0(R)$$

such that $\psi$ is a ring homomorphism and $\theta$ imparts the structure of a $\theta$-algebra on $\pi_0(R)$: $\psi(x) = x^p + p\theta(x)$. We sketch the construction of these two operations here, following [5].

Let $\mathfrak{S}_p$ be the symmetric group on $p$ elements, let $B\mathfrak{S}_{p+}$ denote the unreduced suspension spectrum of its classifying space, and consider its $K(1)$-localization $L_{K(1)}B\mathfrak{S}_{p+}$. There are two natural maps

$$L_{K(1)}B\mathfrak{S}_{p+} \to L_{K(1)}S^0,$$

where $S^0$ is the sphere spectrum. One map arises from the projection to a point $\mathfrak{S}_p \to \{ e \}$; we shall denote it by $\epsilon$. The other map comes from the transfer map; we shall denote it by $Tr$. One can show that the map

$$L_{K(1)}B\mathfrak{S}_{p+} \xrightarrow{(\epsilon, Tr)} L_{K(1)}S^0 \times L_{K(1)}S^0$$
is a weak equivalence.

Define maps

$$\psi', \theta' : L_{K(1)}S^0 \to L_{K(1)}B\mathfrak{S}_p^+$$

in the $K(1)$-local stable homotopy category by requiring that

$$\epsilon(\psi') = 1, \quad \epsilon(\theta') = 0,$$

$$\text{Tr}(\psi') = 0, \quad \text{Tr}(\theta') = -(p - 1)!.$$

The inclusion \{e\} → $\mathfrak{S}_p$ gives rise to a map

$$e : L_{K(1)}S^0 \simeq L_{K(1)}B\{e\}_+ \to L_{K(1)}B\mathfrak{S}_p^+$$

and $\epsilon \circ e = 1$. Moreover, from the Mackey double coset formula, $\text{Tr} \circ e = p!$. It follows that

$$e = \psi' - p\theta'.$$ (1.1)

Let $R$ be a $K(1)$-local $E_\infty$-ring spectrum and let $x \in \pi_0(R)$. The $E_\infty$-ring structure associates to $x$ a map

$$P(x) : L_{K(1)}B\mathfrak{S}_p^+ \to R$$

such that the homotopy class of $P(x) \circ e$ (precomposed by the localization $S^0 \to L_{K(1)}S^0$) is $x^p$. One defines operations

$$\psi, \theta : \pi_0(R) \to \pi_0(R)$$

by taking $\psi(x)$ and $\theta(x)$ to be the homotopy classes of $P(x) \circ \psi'$ and $P(x) \circ \theta'$ respectively. The equation (1.1) then gives us the relation $x^p = \psi(x) - p\theta(x)$. 
In Subsection 2.2, we shall use $\psi$ on a related spectrum to extend $\psi$ to a map $\pi_n(R) \to \pi_n(R)$ for all $n \in \mathbb{N}$. 
1.3 Statement of the Main Results

In terms of modern concepts, forms of the $p$-complete $K$-theory spectrum $K_p$ are defined as follows. One works in the closed symmetric monoidal category of $p$-complete ring spectra. Denote by $S^0_p$ the $p$-complete sphere spectrum, the unit of this category, and by $S^0_{p\infty}$ the unique spectrum satisfying $\pi_*(S^0_{p\infty}) \cong \pi_*(S^0_p) \otimes_{\mathbb{Z}_p} W(F_p)$ on the level of homotopy.

**Definition 1.5.** An $S^0_{p\infty}/S^0_p$-form of $K_p$ is a $p$-complete ring spectrum $R$ such that

$$(K_p \wedge_{S^0_p} S^0_{p\infty})^\wedge_p \cong (R \wedge_{S^0_p} S^0_{p\infty})^\wedge_p.$$  

Note that this definition is dual to that given in Definition 1.1.

The spectrum $K_p$ has a unique $E_{\infty}$-ring structure (up to contractible choice) and is $K(1)$-local. In this dissertation, I demonstrate that $S^0_{p\infty}/S^0_p$-forms of $K_p$ satisfy the same results:

**Theorem 1.6.** The ring structure on every $S^0_{p\infty}/S^0_p$-form of $K_p$ has a unique refinement to an $E_{\infty}$-ring structure.

**Theorem 1.7.** Every $S^0_{p\infty}/S^0_p$-form of $K_p$ is $K(1)$-local.

In practice, forms of $K_p$ which arise from topological modular forms often come equipped with an $E_{\infty}$-ring structure as well as the data $\psi : \pi_2(R) \to \pi_2(R)$, where $\psi$ is the map mentioned in Subsection 1.2 in terms of Hecke operators on modular forms. It is thus desirable to have a method to identify the form of $K_p$ encountered. I further provide a method to distinguish homotopy equivalence classes of $E_{\infty}$-$S^0_{p\infty}/S^0_p$-forms of $K_p$ via a direct computation involving the operation $\psi$ in the second homotopy group of the spectrum:
Theorem 1.8. Let $R$ be an $E_\infty S_p^{0}/S_p^{0}$-form of $K_p$. The operation $\psi : \pi_2(R) \to \pi_2(R)$ satisfies $\psi(x) = \varepsilon px$ for some $\varepsilon \in Z_p^\times$, and the value of the constant $\varepsilon$ determines a bijection between homotopy equivalence classes of $E_\infty S_p^{0}/S_p^{0}$-forms of $K_p$ and $Z_p^\times$. 
2 Main Results

2.1 Preliminaries

Before proving the main results, we recall the theory involving forms of an algebraic structure.

There is the following general principle:

**Principle 2.1** ([12, Chapter III, §1]). Let $K/k$ be a field extension and let $X$ be an object defined over $k$. If $K/k$ is a Galois extension, then there is an injective map

$$\{k\text{-isomorphism classes of } K/k\text{-forms of } X\} \hookrightarrow H^1(\text{Gal}(K/k), \text{Aut}_K(X)),$$

where the Galois group acts by conjugation, which is a bijection in many cases (e.g. when $X$ is a vector space with a $(p,q)$-tensor or a quasiprojective variety).

Moreover, in such a situation, the $K/k$-forms of $X$ can be recovered from $X \times_k K$ by taking the fixed points of or quotient by the action of the Galois group $\text{Gal}(K/k)$ for different actions of $\text{Gal}(K/k)$ on $X \times_k K$.

In the case of $S_{p^\infty}^0/S_{p^\infty}^0$-forms of $K_p$, the situation is as follows [2]:

There is an action of $\text{Aut}(W(\overline{F}_p)/\mathbb{Z}_p) \cong \text{Gal}(\overline{F}_p/F_p)$ on $(K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0)^\wedge$ which acts in the expected manner on homotopy groups. $K_p$ can be recovered as the homotopy fixed points of the action of the Frobenius $\sigma$ which topologically generates $\text{Gal}(\overline{F}_p/F_p)$: there is a homotopy pullback square of ring spectra

$$
\begin{array}{ccc}
K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0 & \rightarrow & (K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0)^\wedge \\
\downarrow & & \downarrow^{(\text{id},\sigma)} \\
(K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0)^\wedge & \xrightarrow{\Delta} & (K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0)^\wedge \times (K_p \wedge_{S_{p^\infty}^0} S_{p^\infty}^0)^\wedge
\end{array}
$$
where $\Delta$ is the diagonal map.

By Goerss-Hopkins-Miller theory [3], the spaces of $E_\infty$-ring automorphisms $\text{Aut}_{E_\infty}(K_p)$ and $\text{Aut}_{E_\infty}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)$ are homotopy discrete and

$$\pi_0(\text{Aut}_{E_\infty}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)) \cong \pi_0(\text{Aut}_{\text{mult}}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)),$$

where $\text{Aut}_{\text{mult}}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)$ denotes the space of multiplicative automorphisms $f : (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge \to (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge$, that is, automorphisms such that the diagram

$$\begin{array}{ccc}
(K_p \wedge_{S_p} S_{p^\infty})_p^\wedge \wedge_{S_p^0} (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge & \longrightarrow & (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge \\
\downarrow f \wedge f & & \downarrow f \\
(K_p \wedge_{S_p} S_{p^\infty})_p^\wedge \wedge_{S_p^0} (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge & \longrightarrow & (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge
\end{array}$$

commutes up to homotopy. These multiplicative automorphisms are in turn in bijection with

$$\text{Hom}_{(K_p \wedge_{S_p} S_{p^\infty})_p^\wedge}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge, (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge ; (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge).$$

One can show that

$$\text{Ext}^s_{(K_p \wedge_{S_p} S_{p^\infty})_p^\wedge}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge, (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge ; (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)$$

vanishes for $s > 0$, so that the universal coefficient theorem implies that

$$\pi_0(\text{Aut}_{E_\infty}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)) \cong ((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge)^* (\text{Ext}^s_{(K_p \wedge_{S_p} S_{p^\infty})_p^\wedge}((K_p \wedge_{S_p} S_{p^\infty})_p^\wedge, (K_p \wedge_{S_p} S_{p^\infty})_p^\wedge))^* \cong \mathbb{Z}_p^* \times \text{Gal}(\overline{F_p}/F_p).$$
On the other hand, there is a short exact sequence

\[ 0 \to \pi_0(\text{Aut}_{E^\infty}(K_p)) \to \pi_0(\text{Aut}_{E^\infty}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \to \pi_0(\text{Aut}_{E^\infty/K_p}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \to 0 \]

where \( \text{Aut}_{E^\infty/K_p}((K_p \wedge S^0_{p^\infty})^\wedge_p) \) are the \( E^\infty \)-ring automorphisms of \((K_p \wedge S^0_{p^\infty})^\wedge_p \) which fix \( K_p \). It is known that \( \pi_0(\text{Aut}_{E^\infty}(K_p)) \) is the Morava stabilizer group \( S_1 \cong \mathbb{Z} \times p \) whose elements are Adams operations \( \psi^\lambda \), where \( \lambda \in \mathbb{Z}^\times_p \). It follows that the short exact sequence splits, so there is an isomorphism

\[ \pi_0(\text{Aut}_{E^\infty}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \cong \pi_0(\text{Aut}_{E^\infty}(K_p)) \times \pi_0(\text{Aut}_{E^\infty/K_p}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \]

and

\[ \pi_0(\text{Aut}_{E^\infty/K_p}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \cong \text{Gal}(\mathbb{F}_p/\mathbb{F}_p). \]

Moreover, the action of the Frobenius is by an \( E^\infty \)-ring map.

Denote the subgroup \( \pi_0(\text{Aut}_{E^\infty/K_p}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \subset \pi_0(\text{Aut}_{E^\infty}((K_p \wedge S^0_{p^\infty})^\wedge_p)) \) by \( \text{Gal}_{K_p} \). We shall write \((K_p \wedge S^0_{p^\infty})^\wedge_p)^{\text{hGal}_{K_p}}\) to denote the above homotopy pullback and call it a homotopy fixed point spectrum.

In general, the different \( S^0_{p^\infty} \, S^0_{p^\infty}/S^0_{p^\infty} \) forms \( R \) of \( K_p \) can be recovered up to homotopy as homotopy pullbacks for twisted versions of \( \sigma \), where one replaces \( \sigma \) by \( \sigma_R = \sigma \circ \psi^\lambda \) for some choice of Adams operation \( \psi^\lambda \in \pi_0(\text{Aut}_{E^\infty}(K_p)) \):

**Lemma 2.2** (Behrens-Lawson [2]). There is a homotopy pullback square

\[
\begin{array}{ccc}
R & \longrightarrow & (K_p \wedge S^0_{p^\infty})^\wedge_p \\
\downarrow & & \downarrow \text{id}_*(\sigma \circ \psi^\lambda) = (\text{id}, \sigma_R) \\
(K_p \wedge S^0_{p^\infty})^\wedge_p & \longrightarrow & (K_p \wedge S^0_{p^\infty})^\wedge_p \times (K_p \wedge S^0_{p^\infty})^\wedge_p.
\end{array}
\]
Moreover, the action of $\sigma_R = \sigma \circ \psi^\lambda$ is by an $E_\infty$-ring map.

Each $\sigma_R$ topologically generates a subgroup $\text{Gal}_R \subset \pi_0(\text{Aut}_{E_\infty}((K_p \wedge_{S_p^0} S_{p^\infty}^0)_p^\wedge))$ which is isomorphic to $\text{Gal}(\overline{\mathbb{F}_p}/\mathbb{F}_p)$, mirroring the situation in Principle 2.1. As before, we shall write $((K_p \wedge_{S_p^0} S_{p^\infty}^0)_p^\wedge)^{h\text{Gal}_R}$ to denote the homotopy pullback defined in this manner and call it a homotopy fixed point spectrum.
2.2 Proofs of the Main Results

We now proceed to prove the results mentioned in Subsection 1.3. For the convenience of the reader, we recall the results here.

**Theorem 2.3.** The ring structure on every $S_p^0 / S_p^0$-form of $K_p$ has a unique refinement to an $E_\infty$-ring structure.

The proof uses the following result.

**Definition 2.4.** An $E_\infty$-$R$-algebra $R'$ is étale if

(a) the map $\pi_0(R) \to \pi_0(R')$ is étale in the sense of ordinary commutative algebra, and

(b) the natural map $\pi_0(R') \otimes_{\pi_0(R)} \pi_*(R) \to \pi_*(R')$ is an isomorphism.

**Theorem 2.5** (Lurie, *Higher Algebra*, Theorem 8.5.4.2). Let $R$ be an $E_\infty$-ring spectrum. The $\infty$-category of étale $E_\infty$-$R$-algebras is equivalent under $\pi_0$ to the nerve of the ordinary category of étale $\pi_0(R)$-algebras.

**Proof of Theorem 2.3.** It is known that $K_p$ has a unique $E_\infty$-ring structure. Firstly, we note that $(K_p \wedge S_p^0 S_p^0)^\wedge_p$ is an étale $E_\infty$-$K_p$-algebra. $(K_p \wedge S_p^0 S_p^0)^\wedge_p$ inherits an $E_\infty$-ring structure from the algebra map and the map

$$Z_p = \pi_0(K_p) \to \pi_0((K_p \wedge S_p^0 S_p^0)^\wedge_p) = W(F_p)$$

is étale by the Jacobian criterion since $W(F_{p^n})$ is an unramified extension of $Z_p$ for each $n \in \mathbf{N}$. By Theorem 2.5, $(K_p \wedge S_p^0 S_p^0)^\wedge_p$ has a unique $E_\infty$-ring structure refining its ring structure because of the uniqueness of the algebra map $\pi_0(K_p) \to \pi_0((K_p \wedge S_p^0 S_p^0)^\wedge_p)$. 

15
As mentioned in Lemma 2.2, every $\mathcal{S}_{p^\infty}/\mathcal{S}_p$-form $R$ of $K_p$ can be recovered up to homotopy as the homotopy fixed point spectrum $((K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p)^{h \text{Gal}_R}$. It follows that $R$ inherits an $E_\infty$-ring structure from $((K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p)^{h \text{Gal}_R}$. $R$ cannot have more than one $E_\infty$-ring structure refining its ring structure since the same would then need to be the case for $(R \wedge \mathcal{S}_{p^\infty})^\wedge_p$.

\begin{theorem}
Every $\mathcal{S}_{p^\infty}/\mathcal{S}_p$-form of $K_p$ is $K(1)$-local.
\end{theorem}

We use the following lemma.

\begin{lemma}
$K_p/p \wedge X$ is $K(1)$-local for any spectrum $X$.
\end{lemma}

\begin{proof}
We use the fact that $K_p/p$ is a wedge of $p-1$ copies of suspensions of $K(1)$. As mentioned in Subsection 1.2, Morava $K$-theory is a field in the category of ring spectra, that is, every module spectrum over $K(n)$ is a wedge of suspensions of $K(n)$. In particular, $K_p/p \wedge X$ is a wedge of suspensions of $K(1)$, so it is $K(1)$-local.
\end{proof}

\begin{proof}[Proof of Theorem 2.6]
Recall that a spectrum $R$ is $E$-local if every map $X \to R$ is nullhomotopic whenever $X$ is $E$-acyclic, that is, $X \wedge E$ is zero.

We proceed by making a series of reductions. First, it suffices to show that $(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p$ is $K(1)$-local, since every $\mathcal{S}_{p^\infty}/\mathcal{S}_p$-form $R$ of $K_p$ is obtained as a homotopy pullback involving $(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p$, so that any map $X \to R$ is nullhomotopic if every map $X \to (K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p$ is also nullhomotopic.

Next, since $(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p$ is $p$-complete, it suffices to show that $(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p/p^n$ is $K(1)$-local for each $n \in \mathbb{N}$, as it will then follow from the universal property of $p$-completion that $(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p$ is also $K(1)$-local.

Finally, since there are fiber sequences

$$(K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p/p \to (K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p/p^n \to (K_p \wedge \mathcal{S}_{p^\infty})^\wedge_p/p^{n-1},$$

16
it in turn suffices to show that \((K_p \wedge S^0_p S^0_{p\infty})^\wedge / p\) is \(K(1)\)-local; \(K(1)\)-locality of \((K_p \wedge S^0_p S^0_{p\infty})^\wedge / p^n\) for \(n \geq 2\) will then follow by induction on \(n\) using the fiber sequences.

The result then follows from Lemma 2.7 since \((K_p \wedge S^0_p S^0_{p\infty})^\wedge / p \simeq K_p / p \wedge S^0_{p\infty}\).\(\square\)

As mentioned in Subsection 1.2, every \(K(1)\)-local \(E_\infty\)-ring spectrum \(R\) possesses operations

\[\theta, \psi : \pi_0(R) \to \pi_0(R)\]

such that \(\psi\) is a ring homomorphism and \(\theta\) imparts the structure of a \(\theta\)-algebra on \(\pi_0(R)\). \([5]\) For any form \(R\) of \(K_p\), the only ring homomorphism \(\pi_0(R) = \mathbb{Z}_p \to \pi_0(R)\) is the identity homomorphism, so \(\psi\) is unable to distinguish forms of \(K_p\). However, one can obtain an operation \(\psi : \pi_2(R) \to \pi_2(R)\) that is able to distinguish forms of \(K_p\), by considering the function spectrum \(R^{S^n}\).

**Lemma 2.8.** If \(R\) is an \(E_\infty\)-ring spectrum and \(Z\) is a space, then the function spectrum \(R^Z\) is also an \(E_\infty\)-ring spectrum.

**Lemma 2.9.** If a spectrum \(R\) is \(Y\)-local, then the function spectrum \(R^{S^n}\) is also \(Y\)-local.

**Proof.** Suppose \(X \wedge Y\) is zero. Then

\[ [X, R^{S^n}] = [\Sigma^n X, R] = 0 \]

since \(R\) is \(Y\)-local. \(\square\)

Consequently, if \(R\) is a \(K(1)\)-local \(E_\infty\)-ring spectrum, then so is \(R^{S^n}\). Hence one obtains operations

\[\psi : \pi_0(R^{S^n}) \to \pi_0(R^{S^n})\].
That is, there are operations \( \pi_n(R) \to \pi_n(R) \) for each \( n \in \mathbb{N} \) which we shall also denote by \( \psi \).

**Theorem 2.10.** Let \( R \) be an \( E_\infty -S^0_{p^\infty}/S^0_p \)-form of \( K_p \). The operation \( \psi : \pi_2(R) \to \pi_2(R) \) satisfies \( \psi(x) = \varepsilon px \) for some \( \varepsilon \in \mathbb{Z}^\times_p \), and the value of the constant \( \varepsilon \) determines a bijection between homotopy equivalence classes of \( E_\infty -S^0_{p^\infty}/S^0_p \)-forms of \( K_p \) and \( \mathbb{Z}^\times_p \).

**Proof.** Recall from Lemma 2.2 that \( R \) can be recovered as the homotopy fixed point spectrum \( ((K_p \wedge S^0_p S^0_{p^\infty})^\wedge_p)^{\text{hGal}}_R \). On the level of homotopy, we obtain from the Mayer-Vietoris sequence

\[
\pi_2(R) = \left\{ x \in \pi_2((K_p \wedge S^0_p S^0_{p^\infty})^\wedge_p) \mid \sigma_R(x) = x \right\}.
\]

Recall that \( \sigma_R = \sigma \circ \psi^\lambda \), where \( \sigma \) is the Frobenius and \( \psi^\lambda \) is an Adams operation on \( K_p \).

Let \( y = 1 - \mathcal{L} \in \pi_2((K_p \wedge S^0_p S^0_{p^\infty})^\wedge_p) \) be a generator of \( \pi_2(K_p) \subset \pi_2((K_p \wedge S^0_p S^0_{p^\infty})^\wedge_p) \), where \( \mathcal{L} \) is the class of the tautological bundle on \( S^2 = \mathbb{C}P^1 \). Recall that \( (1 - \mathcal{L})^2 = 0 \).

Thus

\[
\psi^\lambda(y) = \psi^\lambda(1 - \mathcal{L}) = 1 - \mathcal{L}^\lambda = 1 - (1 - (1 - \mathcal{L}))^\lambda = \lambda(1 - \mathcal{L}) = \lambda y.
\]

Suppose that \( x = \mu y \) where \( \mu \in \pi_0((K_p \wedge S^0_p S^0_{p^\infty})^\wedge_p) \). Then

\[
\mu y = \sigma_R(\mu y) = \sigma \circ \psi^\lambda(\mu y) = \sigma(\mu \psi^\lambda(y)) = \sigma(\mu)\psi^\lambda(y) = \sigma(\mu)\lambda y.
\]

Hence \( \sigma(\mu) = \mu \lambda^{-1} \). Finally, we use the fact that \( \psi \) is Frobenius-linear and, on
\[ \pi_2(K_p), \text{ is induced by the Adams operation } \psi^p. \] It then follows that

\[ \psi(x) = \psi(\mu y) = \sigma(\mu)\psi(y) = \mu \lambda^{-1} py = \lambda^{-1} px. \]

Theorem 2.10 thus provides a way to identify a form of \( K_p \) without recourse to 1-cocycles in the first Galois cohomology group.
3 Future Directions

As noted in Subsection 1.1, concrete forms of $K$-theory which involve the Ramanujan tau function or the quartic residue character arise from elliptic cohomology. I intend to compute the action of $\psi$ on $\pi_2(R)$ in these cases and other examples of interest.

I wish to interpret both existing and new results about forms of $K$-theory in the context of topological modular forms, so as to tie them closer to current research.

By extending topological modular forms to a functorial family of objects corresponding to elliptic curves with level structure and modular forms on them and restricting to the cusps, Hill and Lawson [4] obtain $E_\infty$-ring maps from topological modular forms with level structure to forms of $K$-theory. I am interested in studying the properties of these maps.

Besides considering forms of $K$-theory that arise from topological modular forms, I also hope to consider forms of $K$-theory arising in topological automorphic forms, as in [2].

Being an $E_\infty$-ring spectrum, Morava $E$-theory $E_n$ possesses power operations whose structure has been studied by Ando [1] and Rezk [10]. Rezk has calculated the structure in detail for height two [9, 11]. I hope to use the theory of power operations in Morava $E$-theory to develop analogous criteria to distinguish forms of higher Morava $E$-theory.
References


