

Representation of Quivers

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Chapter 1

Introduction

This project aims to cover interesting topics from the area of quiver representations. The first chapter will give a brief introduction to the topics in Homological Algebra needed for bulk of the report. It will cover chain complexes, exact sequences, short exact sequences, and extensions, most importantly Ext^1 . The the second chapter will introduce quivers and look at some interesting results about path algebras before moving onto representations of quivers and their relationship with the modules of the corresponding path algebra. Next we will cover Dynkin and Euclidean diagrams before finishing with a proof of Gabriel's Theorem. The third chapter will cover Auslander-Reiten quivers.

Chapter 2

Homological Algebra

In this chapter we will be introducing results from Homological Algebra and will mainly be following the first two sections of [1], but with heavy influence from [3] and [4]. We will first explore chain complexes before moving onto exact sequences and extensions before finishing by looking at some results of Ext^1 will be useful later on in the report. For the chapter, we let R be a ring and will be considering left R -modules.

2.1 Chain Complexes

Definition 2.1.1. A *chain complex* \mathbf{C}_\bullet consists of a sequence of R -modules C_i ($i \in \mathbb{Z}$) and morphisms of the form,

$$\mathbf{C} : \quad \dots \xrightarrow{\delta_3} C_2 \xrightarrow{\delta_2} C_1 \xrightarrow{\delta_1} C_0 \xrightarrow{\delta_0} C_{-1} \xrightarrow{\delta_{-1}} C_{-2} \xrightarrow{\delta_{-2}} \dots$$

such that $\delta_{n-1}\delta_n = 0$ for all n , i.e. the composition of any two consecutive maps is zero. The maps δ_n are called the *differentials* of C .

Remark 2.1.2. It is convention that the map δ_n starts at C_n .

Example 2.1.3. If we have a field k then we can create the following chain complex:

$$\mathbf{C} : \quad \dots \rightarrow 0 \rightarrow k^2 \xrightarrow{\begin{pmatrix} 1 & 2 \\ 3 & 0 \\ 0 & 0 \end{pmatrix}} k^3 \xrightarrow{(0 \ 0 \ 1)} k \rightarrow 0 \rightarrow \dots$$

We can clearly see that the maps uphold the $\delta^2 = 0$ condition as,

$$(0 \ 0 \ 1) \begin{pmatrix} 1 & 2 \\ 3 & 0 \\ 0 & 0 \end{pmatrix} = (0 \ 0).$$

Example 2.1.4. If we consider the sequence,

$$\dots \rightarrow 0 \rightarrow k \xrightarrow{\delta_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2 \xrightarrow{\delta_1 = (1 \ 0)} k \rightarrow 0 \rightarrow \dots$$

however,

$$\begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = 1 \neq 0.$$

Hence, $\delta_1\delta_2 \neq 0$, and so the sequence is not a chain complex. However, if we change δ_2 slightly we obtain the chain complex,

$$\mathbf{C} : \quad \dots \rightarrow 0 \rightarrow k \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2 \xrightarrow{\begin{pmatrix} 0 & 1 \end{pmatrix}} k \rightarrow 0 \rightarrow \dots$$

since,

$$\begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = 1 \neq 0.$$

Definition 2.1.5. For a chain complex,

$$\mathbf{C} : \quad \dots \rightarrow C_{n+1} \xrightarrow{\delta_{n+1}} C_n \xrightarrow{\delta_n} C_{n-1} \rightarrow \dots$$

we define:

$$Z_n(\mathbf{C}) = \ker(\delta_n) \quad \& \quad B_n(\mathbf{C}) = \text{im}(\delta_{n+1}).$$

To explore the relationship between $Z_n(\mathbf{C})$ and $B_n(\mathbf{C})$, the following is a solution to Exercise 2.14 in [3]. (Note the example will not be provided here as exactness has not yet been covered.)

Lemma 2.1.6. *Let,*

$$A \xrightarrow{f} B \xrightarrow{g} C,$$

be a sequence of module maps. Then $gf = 0$ if and only if $\text{im}(f) \subseteq \text{im}(g)$.

Proof. Suppose $gf = 0$, i.e., for all $a \in A$, $g(f(a)) = 0$ which implies that $f(a) \in \ker(g)$ for all $a \in A$. Hence, $\text{im}(f) \subseteq \ker(g)$.

Conversely, suppose that $\text{im}(f) \subseteq \ker(g)$. Every element $b \in \text{im}(f)$ is also an element of $\ker(g)$, thus $gf = 0$. \square

Definition 2.1.7. If \mathbf{C} is a chain complex then its *homology* is defined to be,

$$H_n(\mathbf{C}) = \frac{\ker(\delta_n : C_n \rightarrow C_{n-1})}{\text{im}(\delta_{n+1} : C_{n+1} \rightarrow C_n)} = \frac{Z_n(\mathbf{C})}{B_n(\mathbf{C})},$$

which is an R -module.

The subsequent proposition is the solution to Exercise 6.1 in [3].

Proposition 2.1.8. *If \mathbf{C} is a chain complex with $C_n = 0$ for some n then $H_n(\mathbf{C}) = 0$.*

Proof. Well suppose we have such a chain complex,

$$\mathbf{C} : \quad \dots \rightarrow C_{n+1} \xrightarrow{\delta_{n+1}} 0 \xrightarrow{\delta_n} C_{n-1} \rightarrow \dots$$

the the homology is,

$$H_n(\mathbf{C}) = \frac{\ker(\delta_n : 0 \rightarrow C_{n-1})}{\text{im}(\delta_{n+1} : C_{n+1} \rightarrow 0)},$$

as the only element in C_n is the zero element, and so, $H_n(\mathbf{C}) = 0$, as required. \square

Examples 2.1.9 and 2.1.13 are taken from [1] and are included here because they are felt to be the clearest at demonstrating a chain complex and homology, however, the more general statement of the second example is presented as Proposition 2.1.11 because it is an interesting result.

Example 2.1.9. If we take a module M then we can make a chain complex;

$$\mathbf{C} : \quad \dots \rightarrow 0 \rightarrow M \rightarrow 0 \rightarrow \dots$$

where M is at degree n . Then the homology will be:

$$H_i(\mathbf{C}) = \begin{cases} \frac{\ker(M \rightarrow 0)}{\operatorname{im}(0 \rightarrow M)} = M & i = n, \\ 0 & \text{otherwise.} \end{cases}$$

Remark 2.1.10. Recall,

$$\operatorname{Coker}(f) = \frac{\operatorname{Codomain of } f}{\operatorname{Image of } f},$$

is the *cokernel* of the map f .

Proposition 2.1.11. If we have a module homomorphism between R -modules, $f : M \rightarrow N$, then we get the chain complex,

$$\mathbf{C} : \quad \dots \xrightarrow{\deg} 0 \xrightarrow{n+2} M \xrightarrow{n+1} N \xrightarrow{n} 0 \xrightarrow{n-1} \dots,$$

and the homology becomes,

$$H_i(\mathbf{C}) = \begin{cases} \frac{N}{\operatorname{im}(f)} = \operatorname{coker}(f) & i = n \\ \ker(f) & i = n + 1 \\ 0 & \text{otherwise.} \end{cases}$$

Proof. Firstly, at degree n we have that,

$$H_n(\mathbf{C}) = \frac{\ker(N \rightarrow 0)}{\operatorname{im}(M \xrightarrow{f} N)} = \frac{N}{\operatorname{im}(f)} = \operatorname{coker}(f).$$

Then at degree $n + 1$ we have that,

$$H_{n+1}(\mathbf{C}) = \frac{\ker(M \xrightarrow{f} N)}{\operatorname{im}(0 \rightarrow M)} = \ker(f).$$

Finally, it is clear that everywhere else there is no homology. □

Remark 2.1.12. Recall,

$$\operatorname{Coker}(f) = \frac{\operatorname{Codomain of } f}{\operatorname{Image of } f},$$

is the *cokernel* of the map f .

Example 2.1.13. We can have a chain complex of \mathbb{Z} -modules,

$$\mathbf{C} : \quad \begin{array}{ccccccc} \dots & \rightarrow & 0 & \rightarrow & \mathbb{Z} & \xrightarrow{a} & \mathbb{Z} \rightarrow 0 \rightarrow \dots \\ & & \deg & & 2 & & 1 & & 0 & & -1 \end{array}$$

where the map a is right multiplication by some $a \in \mathbb{Z}$. Firstly, we deal with the case where a is not the zero map.

The homology is,

$$H_i(\mathbf{C}) = \begin{cases} \frac{\ker(\mathbb{Z} \xrightarrow{a} 0)}{\operatorname{im}(\mathbb{Z} \xrightarrow{a} \mathbb{Z})} = \frac{\mathbb{Z}}{a\mathbb{Z}} & i = 0, \\ 0 & \text{otherwise.} \end{cases}$$

Note that,

$$H_0(\mathbf{C}) = \frac{\mathbb{Z}}{a\mathbb{Z}} = \frac{\text{Codomain of } f}{\text{Image of } f} = \operatorname{coker}(a).$$

Also,

$$H_1(\mathbf{C}) = \frac{\ker(\mathbb{Z} \xrightarrow{a} \mathbb{Z})}{\operatorname{im}(0 \rightarrow \mathbb{Z})} = \ker(a) = 0,$$

as a is injective.

However, in the instance that a is the zero map, we have that,

$$\ker(\mathbb{Z} \xrightarrow{0} \mathbb{Z}) = \mathbb{Z} \quad \& \quad \operatorname{im}(\mathbb{Z} \xrightarrow{0} \mathbb{Z}) = 0.$$

So,

$$H_0(\mathbf{C}) = \mathbb{Z} \quad \& \quad H_1(\mathbf{C}) = \mathbb{Z},$$

with $H_i(\mathbf{C}) = 0$ for all $i \neq 0, 1$.

Definition 2.1.14. • The elements of $B_n(\mathbf{C})$ are called n -boundaries.

- The elements of $Z_n(\mathbf{C})$ are called n -cycles.

Remark 2.1.15. If $x \in Z_n(\mathbf{C})$ then its image in $H_n(\mathbf{C})$ is usually written as $[x]$.

Definition 2.1.16. A chain complex \mathbf{C} is said to be:

- *acyclic* if $H_n(\mathbf{C}) = 0$ for all n .
- *bounded above* if there exists some $n \in \mathbb{N}$, $C_k = 0$ for all $k > n$.
- *bounded below* if for some $n \in \mathbb{N}$, $C_k = 0$ for all $k < n$.
- *bounded* if it is bounded above and below.
- *non-negative* if $C_n = 0$ for $n < 0$.

Example 2.1.17. Both the chain complexes in the previous examples are bounded both above and below, however, neither is acyclic as they both have instances where the homology is non-zero. The chain complex in Example 2.1.13 is non-negative because $C_n \neq 0$ only when $n = 0, 1$.

Example 2.1.18. If we take another look at the chain complex in Example 2.1.4,

$$\mathbf{C} : \quad \begin{array}{ccccccc} \dots & \rightarrow & 0 & \rightarrow & k & \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} & k^2 & \xrightarrow{\begin{pmatrix} 0 & 1 \end{pmatrix}} & k & \rightarrow & 0 & \rightarrow & \dots \\ \text{deg} & & & & 1 & & 0 & & -1 & & & & \end{array}$$

and we have,

$$\begin{aligned} \ker(k \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2) &= 0 \quad \& \quad \text{im}(0 \rightarrow k) = 0, \\ \ker(k^2 \xrightarrow{\begin{pmatrix} 1 & 0 \end{pmatrix}} k) &\cong 0 \oplus k \cong k \quad \& \quad \text{im}(k \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2) \cong k \oplus 0 \cong k, \\ \ker(k \rightarrow 0) &= k \quad \& \quad \text{im}(k^2 \xrightarrow{\begin{pmatrix} 1 & 0 \end{pmatrix}} k) \cong k \oplus 0 \cong k. \end{aligned}$$

So the homologies are,

$$\begin{aligned} H_1(\mathbf{C}) &= \frac{\ker(k \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2)}{\text{im}(0 \rightarrow k)} = 0, \\ H_0(\mathbf{C}) &= \frac{\ker(k^2 \xrightarrow{\begin{pmatrix} 1 & 0 \end{pmatrix}} k)}{\text{im}(k \xrightarrow{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} k^2)} \cong \frac{k}{k} \cong 0, \\ H_{-1}(\mathbf{C}) &= \frac{\ker(k \rightarrow 0)}{\text{im}(k^2 \xrightarrow{\begin{pmatrix} 1 & 0 \end{pmatrix}} k)} \cong \frac{k}{k} \cong 0. \end{aligned}$$

Thus $H_n(\mathbf{C}) = 0$ for all n and so \mathbf{C} is an acyclic chain complex. Later in the report, we will see that \mathbf{C} is in fact a short exact sequence.

Example 2.1.19. The chain complex,

$$\mathbf{C} : \quad \begin{array}{ccccccc} \dots & \xrightarrow{3} & \frac{\mathbb{Z}}{9\mathbb{Z}} & \xrightarrow{3} & \frac{\mathbb{Z}}{9\mathbb{Z}} & \xrightarrow{3} & \frac{\mathbb{Z}}{9\mathbb{Z}} & \rightarrow & \dots \\ \text{deg} & & 1 & & 0 & & -1 & & \end{array}$$

where the differentials are the maps,

$$\delta_n : \frac{\mathbb{Z}}{9\mathbb{Z}} \rightarrow \frac{\mathbb{Z}}{9\mathbb{Z}}, \quad z + 9\mathbb{Z} \mapsto 3z + 9\mathbb{Z},$$

is unbounded. It is also acyclic, since $\ker(\delta_n : \mathbb{Z}/9\mathbb{Z} \rightarrow \mathbb{Z}/9\mathbb{Z}) = \text{im}(\delta_n : \mathbb{Z}/9\mathbb{Z} \rightarrow \mathbb{Z}/9\mathbb{Z})$ as they are both equal to the subset $\{0, 3, 6\}$ of $\mathbb{Z}/9\mathbb{Z}$. So the homology is,

$$H_n(\mathbf{C}) = \frac{\ker(\delta_n : \frac{\mathbb{Z}}{9\mathbb{Z}} \rightarrow \frac{\mathbb{Z}}{9\mathbb{Z}})}{\text{im}(\delta_n : \frac{\mathbb{Z}}{9\mathbb{Z}} \rightarrow \frac{\mathbb{Z}}{9\mathbb{Z}})} \cong 0,$$

for all n .

Definition 2.1.20. A *cochain complex* \mathbf{C}^\bullet consists of a sequence of R -modules C^i ($i \in \mathbb{Z}$) and morphisms of the form,

$$\mathbf{C} : \quad \dots \xrightarrow{\delta^{-3}} C^{-2} \xrightarrow{\delta^{-2}} C^{-1} \xrightarrow{\delta^{-1}} C^0 \xrightarrow{\delta^0} C^1 \xrightarrow{\delta^1} C^2 \xrightarrow{\delta^2} \dots$$

such that $\delta^{n-1}\delta^n = 0$ for all n , i.e. the composition of any two consecutive maps is zero.

Remark 2.1.21. Chain and cochain complexes can be thought of as almost identical constructs with the only difference being the numbering of the chain. The degree of a chain complex *decreases* from left to right, whereas, the degree of a cochain complex *increases* from left to right. So, we can compute one from the other by setting $C^{-n} = C_n$, or equivalently $C^n = C_{-n}$; this is called *renumbering*.

Definition 2.1.22. If \mathbf{C} is a cochain complex then its *cohomology* is defined to be,

$$H^n(\mathbf{C}) = \frac{\ker(\delta^n : C^n \rightarrow C^{n+1})}{\operatorname{im}(\delta^{n-1} : C^{n-1} \rightarrow C^n)} = \frac{Z^n(\mathbf{C})}{B^n(\mathbf{C})}.$$

- The elements of $B^n(\mathbf{C})$ are called *n-coboundaries*.
- The elements of $Z^n(\mathbf{C})$ are called *n-cocycles*.

Example 2.1.23. We can renumber the chain complex in Example 2.1.13 to get the cochain complex,

$$\mathbf{C} : \quad \begin{array}{ccccccc} \dots & \rightarrow & 0 & \rightarrow & \mathbb{Z} & \xrightarrow{a} & \mathbb{Z} \rightarrow 0 \rightarrow \dots \\ \text{deg} & & -2 & & -1 & & 0 \end{array}$$

Its cohomology is,

$$H^i(\mathbf{C}) = \begin{cases} \frac{\ker(\mathbb{Z} \rightarrow 0)}{\operatorname{im}(\mathbb{Z} \xrightarrow{a} \mathbb{Z})} = \frac{\mathbb{Z}}{a\mathbb{Z}} & i = 0, \\ 0 & \text{otherwise.} \end{cases}$$

Definition 2.1.24. Let \mathbf{C} be a chain complex of left R -modules. If M is a left R -module then $\operatorname{Hom}(\mathbf{C}, M)$ is the cochain complex where,

$$\operatorname{Hom}(\mathbf{C}, M)^n = \operatorname{Hom}(C_n, M),$$

and the differentials,

$$\delta^n : \operatorname{Hom}(\mathbf{C}, M)^n \rightarrow \operatorname{Hom}(\mathbf{C}, M)^{n+1},$$

are induced by the differentials of \mathbf{C} , $\delta_n : C_{n+1} \rightarrow C_n$. The cohomology of this cochain complex is denoted $H^n(\mathbf{C}, M)$.

The following example is a generalised version of one found in [1].

Example 2.1.25. Consider the acyclic chain complex,

$$\mathbf{C} : \quad \begin{array}{ccccccc} \dots & \rightarrow & 0 & \rightarrow & \mathbb{Z} & \xrightarrow{n} & \mathbb{Z} \xrightarrow{\text{nat}} \frac{\mathbb{Z}}{n\mathbb{Z}} \rightarrow 0 \rightarrow \dots \\ \text{deg} & & & & 1 & & 0 \end{array}$$

So applying $\operatorname{Hom}(-, \mathbb{Z})$ gives $\operatorname{Hom}(\mathbb{Z}/n\mathbb{Z}, \mathbb{Z}) = 0$ and $\operatorname{Hom}(\mathbb{Z}, \mathbb{Z}) \cong \mathbb{Z}$ and so $\operatorname{Hom}(\mathbf{C}, \mathbb{Z})$ is the cochain complex,

$$\begin{array}{ccccccc} \dots & \rightarrow & 0 & \rightarrow & \mathbb{Z} & \xrightarrow{n} & \mathbb{Z} \rightarrow 0 \rightarrow \dots \\ \text{deg} & & & & -1 & & 0 \end{array}$$

which has cohomology,

$$H^i(\mathbf{C}, \mathbb{Z}) = \begin{cases} \frac{\ker(\mathbb{Z} \rightarrow 0)}{\operatorname{im}(\mathbb{Z} \xrightarrow{n} \mathbb{Z})} \cong \frac{\mathbb{Z}}{n\mathbb{Z}} & i = 0, \\ 0 & \text{otherwise.} \end{cases}$$

Notice that despite the chain complex being acyclic, its cohomology induced by $\operatorname{Hom}(-, \mathbb{Z})$ is not zero everywhere.

Definition 2.1.26. A *chain map* $f : \mathbf{C} \rightarrow \mathbf{D}$, with \mathbf{C} and \mathbf{D} chain complexes, is given by a homomorphism $f_n : \mathbf{C}_n \rightarrow \mathbf{D}_n$ for each n , such that each square in the following diagram commutes,

$$\begin{array}{ccccccc} \cdots & \xrightarrow{\gamma_{n+2}} & \mathbf{C}_{n+1} & \xrightarrow{\gamma_{n+1}} & \mathbf{C}_n & \xrightarrow{\gamma_n} & \mathbf{C}_{n-1} \xrightarrow{\gamma_{n-1}} \cdots \\ & & \downarrow f_{n+1} & & \downarrow f_n & & \downarrow f_{n-1} \\ \cdots & \xrightarrow{\delta_{n+2}} & \mathbf{D}_{n+1} & \xrightarrow{\delta_{n+1}} & \mathbf{D}_n & \xrightarrow{\delta_n} & \mathbf{D}_{n-1} \xrightarrow{\delta_{n-1}} \cdots \end{array}$$

Note that there is an equivalent notion of a *cochain map* of cochain complexes.

Example 2.1.27. If we have the following diagram,

$$\begin{array}{ccccccccccc} \mathbf{C}: & \cdots & \longrightarrow & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{n} & \mathbb{Z} & \xrightarrow{\text{nat}} & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow & 0 & \longrightarrow & \cdots \\ & & & \parallel & & \downarrow f_1 & \text{nat} & \downarrow f_0 & \text{nat} & \downarrow f_{-1} & & \parallel & & \\ \mathbf{D}: & \cdots & \longrightarrow & 0 & \longrightarrow & \frac{\mathbb{Z}}{n\mathbb{Z}} & \xrightarrow{n} & \frac{\mathbb{Z}}{n^2\mathbb{Z}} & \xrightarrow{\text{nat}} & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow & 0 & \longrightarrow & \cdots \end{array}$$

then we can see that our non trivial chain maps are,

$$\begin{aligned} f_1 : \mathbb{Z} &\rightarrow \frac{\mathbb{Z}}{n\mathbb{Z}}, & z &\mapsto z + n\mathbb{Z}, \\ f_0 : \mathbb{Z} &\rightarrow \frac{\mathbb{Z}}{n^2\mathbb{Z}}, & z &\mapsto z + n^2\mathbb{Z}, \\ f_{-1} : \frac{\mathbb{Z}}{n\mathbb{Z}} &\rightarrow \frac{\mathbb{Z}}{n\mathbb{Z}}, & z + n\mathbb{Z} &\mapsto z + n\mathbb{Z}, \end{aligned}$$

and they satisfy,

$$f_0(\gamma_1(z)) = f_0(nz) = nz + n\mathbb{Z} = 0 \quad \& \quad \delta_1(f_1(z)) = \delta_1(z + n\mathbb{Z}) = nz + n\mathbb{Z} = 0.$$

Simmilarly, we can see that the other chain maps make the diagram commute.

2.2 Exact Sequences

Definition 2.2.1. A finite or infinite sequence of R -morphisms and left R -modules,

$$\cdots \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow \cdots$$

is said to be *exact* at M if $\text{im} f = \ker g$. A finite or infinite sequence of R -morphisms and left R -modules,

$$\cdots \xrightarrow{f_{n+2}} M_{n+1} \xrightarrow{f_{n+1}} M_n \xrightarrow{f_n} M_{n-1} \xrightarrow{f_{n-1}} \cdots$$

is said to be an *exact sequence* if it is exact at every M_i , i.e. $\text{im} f_i = \ker f_{i+1}$.

Example 2.2.2. The finite sequence,

$$0 \rightarrow k \xrightarrow{f} k^2 \xrightarrow{g} k^2 \xrightarrow{h} k^2 \rightarrow 0,$$

where $f(x) = (x, 0)$, $g(x, y) = (0, y)$, and $h(x, y) = (x, 0)$ is an exact sequence since $\text{im}(f) = \{(x, 0) : x \in k\} = \ker(g)$ and $\text{im}(g) = \{(0, y) : y \in k\} = \ker(h)$. However, if we instead consider the finite sequence,

$$0 \rightarrow k \xrightarrow{f} k^2 \xrightarrow{g} k^2 \xrightarrow{h'} k^2 \rightarrow 0,$$

where f and g are the same as above, but $h'(x, y) = (x, y)$. Obviously, once again we have that $\text{im}(f) = \ker(g)$ and $\text{im}(g) = \{(0, y) : y \in k\}$, however, $\ker(h') = \{(0, 0)\}$ and so $\text{im}(g) \neq \ker(h')$. Hence this is not an exact sequence, because it is not exact everywhere.

Definition 2.2.3. A *short exact sequence* is an exact sequence of the form,

$$0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0.$$

This is also referred to as an *extension of N by L* .

Example 2.2.4. The sequence,

$$0 \rightarrow k \xrightarrow{f} k^2 \xrightarrow{g} k \rightarrow 0,$$

where $f(x) = (x, 0)$ and $g(x, y) = y$ is a short exact sequence, since $\text{im}(f) = \{(x, 0) : x \in k\} = \ker(g)$.

Example 2.2.5. Notice that the sequence,

$$0 \rightarrow \mathbb{Z} \xrightarrow{f} \mathbb{Z} \xrightarrow{\eta} \frac{\mathbb{Z}}{3\mathbb{Z}} \rightarrow 0,$$

has $\ker(\eta) = \{z : z + 3\mathbb{Z} = 0\} \cong 3\mathbb{Z}$ and $\text{im}(f) = \{6z : z \in \mathbb{Z}\} \cong 6\mathbb{Z}$. Hence, as $6\mathbb{Z} \subsetneq 3\mathbb{Z}$, $\text{im}(f) \neq \ker(\eta)$ and the sequence is not exact.

Notice that you can obtain a chain complex from an exact sequence simply by deciding the degree of any term of the sequence. To consider the result when a chain complex is an exact sequence, the following is in response to Exercise 1.1.5 from [4]. (Note that the third condition has been omitted as we are not consider quasi-isomerism in this report.)

Theorem 2.2.6. *The following are equivalent for every chain complex \mathbf{C} :*

1. \mathbf{C} is an exact sequence, that is, exact at every C_n .
2. \mathbf{C} is acyclic, that is, $H_n(\mathbf{C}) = 0$ for all n .

Proof. Suppose the chain complex,

$$\mathbf{C} : \quad \dots \rightarrow C_{n+1} \xrightarrow{\delta_{n+1}} C_n \xrightarrow{\delta_n} C_{n-1} \xrightarrow{\delta_{n-1}} \dots$$

is an exact sequence, so we have that $\text{im}(\delta_{n+1}) = \ker(\delta_n)$ for all n , i.e. $B_n(\mathbf{C}) = Z_n(\mathbf{C})$ for all n . Hence, when we compute the homology of \mathbf{C} , we find that,

$$H_n(\mathbf{C}) = \frac{Z_n(\mathbf{C})}{B_n(\mathbf{C})} = 0 \quad \forall n.$$

Thus, \mathbf{C} is acyclic.

Conversely, suppose \mathbf{C} is acyclic, then we have that $H_n(\mathbf{C}) = 0$ for all n . Therefore, $Z_n(\mathbf{C})/B_n(\mathbf{C}) = 0$ for all n , by definition, but this is only possible if either $Z_n(\mathbf{C}) \subset B_n(\mathbf{C})$, which is impossible from Definition 2.1.6, or $Z_n(\mathbf{C}) = B_n(\mathbf{C})$. Thus, $\ker(\delta_n) = \text{im}(\delta_{n+1})$ and so \mathbf{C} is exact. \square

Remark 2.2.7. The above theorem makes it clear that exact sequences can be thought of as acyclic chain complexes. By the same token, homology can be thought of as a chain complex's deviation from exactness.

The following is provided as an example in [6], however, it was felt too useful as a method of constructing exact sequences to be simply an example and so is presented on this report as a lemma.

Proposition 2.2.8. *The sequence,*

$$0 \rightarrow \ker(f) \xrightarrow{\iota} M \xrightarrow{f} N \xrightarrow{\eta} \text{coker}(f) \rightarrow 0,$$

where ι, η are the inclusion, and natural maps respectively, is exact. In addition the sequence,

$$0 \rightarrow \ker(f) \xrightarrow{\iota} M \xrightarrow{\eta} \frac{M}{\text{im}(f)} \rightarrow 0,$$

is a short exact sequence.

Proof. It is clear here that we have $\text{im}(\iota) = \ker(f)$ as ι is the inclusion map and since $\text{coker}(f) = N/\text{im}(f)$ we also have that $\text{im}(f) = \ker(\eta)$. Hence the sequence is exact. The second result follows a similar argument. \square

Example 2.2.9. Consider the map $f : \mathbb{Z}^2 \rightarrow \mathbb{Z}$, $(x, y) \mapsto 2x$. Then $\ker(f) = \{(0, y) : y \in \mathbb{Z}\} \cong \mathbb{Z}$, and $\text{im}(f) = 2\mathbb{Z}$ giving that $\text{coker}(f) = \frac{\mathbb{Z}}{2\mathbb{Z}}$. It follows from Lemma 2.2.8 that the sequence,

$$0 \rightarrow \mathbb{Z} \xrightarrow{\iota} \mathbb{Z}^2 \xrightarrow{f} \mathbb{Z} \xrightarrow{\eta} \frac{\mathbb{Z}}{2\mathbb{Z}} \rightarrow 0,$$

is exact. In addition, the following is a short exact equation,

$$0 \rightarrow \mathbb{Z} \xrightarrow{\iota} \mathbb{Z}^2 \xrightarrow{\eta} \frac{\mathbb{Z}}{2\mathbb{Z}} \rightarrow 0.$$

Here are some simple properties of exact sequences as detailed by Rotman in Proposition 2.18 of [3]. Also included is the solution to Exercise 2.16 (ii) from [3]; it caught our attention as an interesting property, with such a simple proof, which shows the rigidity of the exactness condition.

Proposition 2.2.10. (i) *A sequence $0 \rightarrow L \xrightarrow{f} M$ is exact if and only if f is injective.*

(ii) *A sequence $M \xrightarrow{g} N \rightarrow 0$ is exact if and only if g is surjective.*

(iii) *A sequence $0 \rightarrow L \xrightarrow{h} M \rightarrow 0$ is exact if and only if h is an isomorphism.*

(iv) *If $L \xrightarrow{f} M \xrightarrow{g} N \xrightarrow{h} L'$ then f is surjective if and only if h is injective.*

Proof. (i) As the image of $0 \rightarrow L$ is $\{0\}$, exactness gives $\ker(f) = \{0\}$, and so f is injective. Conversely, given some map $f : L \rightarrow M$, there is an exact sequence $\ker(f) \xrightarrow{\iota} L \rightarrow fM$, where ι is the inclusion map, (see Proposition 2.2.8). If f is injective, then $\ker(f) = \{0\}$.

(ii) The kernel of $N \rightarrow 0$ is N , so the exactness gives $\operatorname{im}(g) = N$, and so g is surjective. Conversely, given $g : M \rightarrow N$, there is an exact sequence $M \xrightarrow{g} N \xrightarrow{\pi} \operatorname{coker}(g)$, where π is the natural map, (see Proposition 2.2.8). If g is surjective, then $N = \operatorname{im}(g)$ and $\operatorname{coker}(g) = \{0\}$.

(iii) Part (i) shows that the sequence is exact at L if and only if h is injective, and part (ii) shows that the sequence is exact at M if and only if h is surjective. Therefore, the sequence is exact everywhere if and only if h is an isomorphism.

(iv) Suppose f is surjective, then $\operatorname{im}(f) = M$, and exactness at M gives $\ker(g) = M$. Hence, $\operatorname{im}(g) = \{0\}$, and exactness at N gives $\ker(h) = \{0\}$ and so h is injective. The converse is similar. \square

Definition 2.2.11. Two short exact sequences,

$$\mathbf{E} : 0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0 \quad \& \quad \mathbf{E}' : 0 \rightarrow L \rightarrow M' \rightarrow N \rightarrow 0,$$

are *equivalent* if there is a map $\xi : M \rightarrow M'$ such that the diagram,

$$\begin{array}{ccccccccc} \mathbf{E}: & 0 & \longrightarrow & L & \longrightarrow & M & \longrightarrow & N & \longrightarrow & 0 \\ & & & \parallel & & \downarrow \xi & & \parallel & & \\ \mathbf{E}': & 0 & \longrightarrow & L & \longrightarrow & M' & \longrightarrow & N & \longrightarrow & 0 \end{array}$$

commutes.

The equivalence classes of extensions of N by L will be represented as $e(N, L)$.

Example 2.2.12. Consider the two short exact sequences,

$$\mathbf{E} : 0 \rightarrow k \xrightarrow{f} k^2 \xrightarrow{g} k \rightarrow 0 \quad \& \quad \mathbf{E}' : 0 \rightarrow k \xrightarrow{f'} k^2 \xrightarrow{g'} k \rightarrow 0,$$

where $f : x \mapsto (x, 0)$, $g : (x, y) \mapsto y$, $f' : x \mapsto (0, x)$ and $g' : (x, y) \mapsto x$. Then we can construct the diagram:

$$\begin{array}{ccccccccc} \mathbf{E}: & 0 & \longrightarrow & k & \longrightarrow & k^2 & \longrightarrow & k & \longrightarrow & 0 \\ & & & \parallel & & \downarrow \xi & & \parallel & & \\ \mathbf{E}': & 0 & \longrightarrow & k & \longrightarrow & k^2 & \longrightarrow & k & \longrightarrow & 0 \end{array}$$

This diagram commutes when ξ is the map $\xi : k^2 \rightarrow k^2$, $(x, y) \mapsto (y, x)$, hence these two short exact equations are equivalent.

For a nonexample we turn to Exercise III 1.1 in [5].

Example 2.2.13. Consider the two short exact sequences,

$$\mathbf{E}: 0 \rightarrow \mathbb{Z} \xrightarrow{f} \mathbb{Z} \xrightarrow{g} \frac{\mathbb{Z}}{3\mathbb{Z}} \rightarrow 0 \quad \& \quad \mathbf{E}': 0 \rightarrow \mathbb{Z} \xrightarrow{f'} \mathbb{Z} \xrightarrow{g'} \frac{\mathbb{Z}}{3\mathbb{Z}} \rightarrow 0,$$

where $f, f' : x \mapsto 3x$, $g : x \mapsto x(\bmod 3)$ and $g' : x \mapsto 2x(\bmod 3)$. Then we can construct the diagram:

$$\begin{array}{ccccccc} \mathbf{E}: & 0 & \longrightarrow & \mathbb{Z} & \longrightarrow & \mathbb{Z} & \longrightarrow & \frac{\mathbb{Z}}{3\mathbb{Z}} & \longrightarrow & 0 \\ & & & \parallel & & \downarrow \xi & & \parallel & & \\ \mathbf{E}': & 0 & \longrightarrow & \mathbb{Z} & \longrightarrow & \mathbb{Z} & \longrightarrow & \frac{\mathbb{Z}}{3\mathbb{Z}} & \longrightarrow & 0 \end{array}$$

Assume \mathbf{E} and \mathbf{E}' are equivalent, so we there must exist some ξ such that the diagram commutes. The second square in the diagram will commute if and only if $\xi = id_{\mathbb{Z}}$, since $f = f'$, however, this then means the third square will never commute, as $g \neq g'$. Thus no such ξ exists and the two short exact sequences are not equivalent.

For the discussion of split exact sequences, this report will first follow [6] in defining a section and retraction and then use Schiffler's Proposition 1.8 to prove that the conditions in Definition 1.23 in [1] are equivalent. This will obtain us the Splitting Lemma. However, the proof of Proposition 1.8 will be omitted as it is

Definition 2.2.14. • A map $f : L \rightarrow M$ is called a *section* if there exists a map $h : M \rightarrow L$ such that $hf = id_L$.

• A map $g : M \rightarrow N$ is called a *retraction* if there exists a map $h : N \rightarrow M$ such that $gh = id_N$.

Definition 2.2.15. A short exact sequence,

$$0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

is said to be *split* if f is a section.

Lemma 2.2.16. (*Splitting Lemma*) If the short exact sequence,

$$0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

is split then the following equivalent conditions hold:

- (i) f is a section.
- (ii) g is a retraction.
- (iii) $im(f)$ is a direct summand of M .

Proof. Proof omitted. See Proposition 1.8 in [6] and the proof given on [7]. \square

Example 2.2.17. The short exact sequence,

$$0 \rightarrow \mathbb{Z} \xrightarrow{f} \mathbb{Z}^2 \xrightarrow{g} \mathbb{Z} \rightarrow 0,$$

where $f : x \mapsto (x, 0)$ and $g : (x, y) \mapsto y$, splits. Then

- (i) f is a section as the map $h : \mathbb{Z}^2 \rightarrow \mathbb{Z}$, $(x, y) \mapsto x$ satisfies $hf = id_{\mathbb{Z}}$.
- (ii) g is a retraction as the map $h' : \mathbb{Z} \rightarrow \mathbb{Z}^2$, $y \mapsto (x, y)$ satisfies $gh = id_{\mathbb{Z}}$.
- (iii) $im(f) \cong \mathbb{Z}$ is a direct summand of $\mathbb{Z}^2 \cong \mathbb{Z} \oplus \mathbb{Z}$.

Rather than provide the following result as a proposition and prove it directly as Rotman does in [3], it will be given as a corollary of the splitting lemma as in [6].

Corollary 2.2.18. *If the sequence,*

$$0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

is split exact, then

$$M \cong L \oplus N.$$

Proof. Since f is injective as the sequence is short exact, we have $L \cong im(f) \cong ker(g)$. The since g is surjective as the sequence is short exact, the first isomorphism theorem implies $N \cong M/ker(g)$. Then Lemma 2.2.16 gives M is a direct summand of $im(f)$, hence, $M \cong L \oplus N$. \square

Example 2.2.19. Notice that in the previous example $\mathbb{Z} \cong im(f) \cong ker(g)$ and $\mathbb{Z} \cong \mathbb{Z}^2/ker(g) \cong \mathbb{Z}$. Hence, $\mathbb{Z}^2 \cong \mathbb{Z} \oplus \mathbb{Z}$, as expected.

Lemma 2.2.20. *If any two extensions of N by L are split, then they are equivalent.*

Proof. Let,

$$\begin{array}{lcl} \mathbf{E}: & 0 & \longrightarrow L \xrightarrow{f} M \xrightarrow{g} N \longrightarrow 0 \\ \& & \\ \mathbf{E}': & 0 & \longrightarrow L \xrightarrow{f'} M' \xrightarrow{g'} N \longrightarrow 0 \end{array}$$

be two split extensions of N by L . Then Corollary 2.2.18 gives $M \cong L \oplus N$ and $M' \cong L \oplus N$ and so there exists some isomorphism $M \cong M'$. \square

Remark 2.2.21. Notice also that if \mathbf{E}, \mathbf{E}' are equivalent extensions and one is split, then the other is also split.

Proof. As the extensions are equivalent we have the commutative diagram,

$$\begin{array}{ccccccc} \mathbf{E}: & 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} N \longrightarrow 0 \\ & & & \parallel & \swarrow \exists r & \downarrow \phi & \parallel \\ \mathbf{E}': & 0 & \longrightarrow & L & \xrightarrow{f'} & M' & \xrightarrow{g'} N \longrightarrow 0 \end{array}$$

As \mathbf{E} splits, f must be a section and so there exists a map $r : M \rightarrow L$ such that $rf = id_L$. Then if $m' \in M'$ it can be mapped to some $\phi^{-1}(m') = m$ as ϕ is an isomorphism by equivalence, and so has an inverse. Hence f' is a sections as there is the map, $r' : M' \rightarrow L$, $m' \mapsto r(\phi^{-1}(m'))$. Thus \mathbf{E}' is split. \square

Definition 2.2.22. Given a short exact sequence,

$$\mathbf{E} : \quad 0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

and a map $\theta : L \rightarrow L'$ then the short exact sequence,

$$\mathbf{E}' : \quad 0 \rightarrow L' \xrightarrow{f'} M' \xrightarrow{g'} N \rightarrow 0,$$

fitting into the commutative diagram

$$\begin{array}{ccccccccc} \mathbf{E}: & 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & N & \longrightarrow & 0 \\ & & & \downarrow \theta & & \downarrow \phi & & \parallel & & \\ \mathbf{E}': & 0 & \longrightarrow & L' & \xrightarrow{f'} & M' & \xrightarrow{g'} & N & \longrightarrow & 0 \end{array}$$

is defined to be the *pushout of \mathbf{E} along θ* .

Proposition 2.2.23. Let \mathbf{E} , \mathbf{E}' and $\theta : L \rightarrow L'$ be defined as above in Definition 2.2.22. Then the pushout of \mathbf{E} along θ exists and is unique up to equivalence.

Proof. Existence: Firstly, set

$$M' = \frac{(L' \oplus M)}{\{(\theta(l), -f(l)) : l \in L\}},$$

and let the maps be $f' : l' \mapsto \overline{(l', 0)}$, $g' : \overline{(l', m)} \mapsto g(m)$ and $\phi : m \mapsto \overline{(0, m)}$, where $\overline{(l', m)}$ denotes the class of $(l', m) \in L' \oplus M$ in M' . The diagram is then commutative as $\phi(f(l)) = \overline{(0, f(l))} = \overline{(0, 0)} = \overline{(\theta(l), 0)} = f'(\theta(l))$ for an $l \in L$ and $id_N(g(m)) = g(m) = g'(\theta(m))$ for any $m \in M$. The pushout is exact as $im(f') = \{\overline{(l', 0)} : l' \in L'\} = ker(g')$.

Uniqueness: The sequence

$$\xi' : \quad 0 \rightarrow L \xrightarrow{\begin{pmatrix} \theta \\ -f \end{pmatrix}} L' \oplus M \xrightarrow{(f' \ \phi)} M' \rightarrow 0,$$

is exact as $im(\begin{pmatrix} \theta \\ -f \end{pmatrix}) = \{\begin{pmatrix} \theta(l) \\ -f(l) \end{pmatrix} : l \in L\} = ker((f' \ \phi))$. Exactness then implies that $(f' \ \phi)$ is surjective and so by the first isomorphism theorem (see proof of Corollary 2.2.18) we have,

$$M' \cong \frac{L' \oplus M}{ker((f' \ \phi))} \cong \frac{L' \oplus M}{\{(\theta(l), -f(l)) : l \in L\}}.$$

This gives equivalence between \mathbf{E}' and \mathbf{E}'' . \square

Example 2.2.24. Consider the short exact sequence,

$$\mathbf{E} : \quad 0 \rightarrow \mathbb{Z} \xrightarrow[n]{f} \mathbb{Z} \xrightarrow[g]{nat} \frac{\mathbb{Z}}{n\mathbb{Z}} \rightarrow 0,$$

and the \mathbb{Z} -module map $\theta : \mathbb{Z} \rightarrow \mathbb{Z}/n\mathbb{Z}$ is the natural one. Now we can use Proposition 2.2.23 to construct the pushout of \mathbf{E} along θ .

Firstly, construct the commutative diagram,

$$\begin{array}{ccccccc} \mathbf{E}: & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow[n]{f} & \mathbb{Z} & \xrightarrow[g]{nat} & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow & 0 \\ & & & \downarrow \theta & & \downarrow \phi & & \parallel & & \\ \mathbf{E}': & 0 & \longrightarrow & \frac{\mathbb{Z}}{n\mathbb{Z}} & \xrightarrow{f'} & M' & \xrightarrow{g'} & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow & 0 \end{array}$$

and now we want to find M' . As $\theta : x \mapsto x + n\mathbb{Z}$ and $f : x \mapsto nx$, we have,

$$M' = \frac{\frac{\mathbb{Z}}{n\mathbb{Z}} \oplus \mathbb{Z}}{\{(x + n\mathbb{Z}, -nx) : x \in \mathbb{Z}\}},$$

and we can set $f' : \mathbb{Z}/n\mathbb{Z} \rightarrow M'$, $x + n\mathbb{Z} \mapsto \overline{(x + n\mathbb{Z}, 0)}$, $g' : M' \rightarrow \mathbb{Z}/n\mathbb{Z}$, $\overline{(x + n\mathbb{Z}, y)} \mapsto y + n\mathbb{Z}$, and $\phi : \mathbb{Z} \rightarrow M'$, $x \mapsto \overline{(0, x)}$. It is clear that this makes the above diagram commutative and gives \mathbf{E}' exact. Furthermore, the map ϕ is onto as,

$$\begin{aligned} M' \ni \overline{(x + n\mathbb{Z}, y)} &= \overline{(x + n\mathbb{Z}, -nx)} + \overline{(0, y + nx)}, \\ &= \overline{(0, y + nx)} \in \text{im}(\phi). \end{aligned}$$

We can also see that,

$$\begin{aligned} \ker(\phi) &= \{y \in \mathbb{Z} : \overline{(0, y)} = 0\}, \\ &= \{y \in \mathbb{Z} : \overline{(0, y)} \text{ is of the form } \overline{(x + n\mathbb{Z}, -nx)}\}, \\ &= \{y \in \mathbb{Z} : n|y, x = \frac{-y}{n} \text{ and } x + n\mathbb{Z} = 0\}, \\ &= \{y \in \mathbb{Z} : n^2|y\} \cong n^2\mathbb{Z}, \end{aligned}$$

and then the First Isomorphism Theorem gives,

$$M' \cong \frac{\mathbb{Z}}{\ker(\phi)} \cong \frac{\mathbb{Z}}{n^2\mathbb{Z}}.$$

Hence, the pushout of \mathbf{E} along θ is,

$$\mathbf{E}' : \quad 0 \rightarrow \frac{\mathbb{Z}}{n\mathbb{Z}} \xrightarrow{f'} \frac{\mathbb{Z}}{n^2\mathbb{Z}} \xrightarrow{g'} \frac{\mathbb{Z}}{n\mathbb{Z}} \rightarrow 0,$$

with the maps f', g' defined as above.

Definition 2.2.25. Given a short exact sequence,

$$\mathbf{E} : \quad 0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

and a map $\psi : N'' \rightarrow N$ then the short exact sequence,

$$\mathbf{E}'' : \quad 0 \rightarrow L \xrightarrow{f''} M'' \xrightarrow{g''} N'' \rightarrow 0,$$

fitting into the commutative diagram

$$\begin{array}{ccccccccc} \mathbf{E}'': & 0 & \longrightarrow & L & \xrightarrow{f''} & M'' & \xrightarrow{g''} & N'' & \longrightarrow & 0 \\ & & & \parallel & & \downarrow \phi' & & \downarrow \psi & & \\ \mathbf{E}: & 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & N & \longrightarrow & 0 \end{array}$$

is defined to be the *pullback* of \mathbf{E} along ψ .

Proposition 2.2.26. *Let \mathbf{E} , \mathbf{E}'' and $\psi : N'' \rightarrow N$ be defined as above in Definition 2.2.25. Then the pullback of \mathbf{E} along ψ exists and is unique up to equivalence.*

Proof. Existence: Firstly, set

$$M'' = \{(m, n'') \in M \oplus N'' : g(m) = \psi(n'')\},$$

and let the maps be $f'' : L \rightarrow M''$, $l \mapsto (f(l), 0)$ (if $g(f(l)) = \psi(0)$, 0 otherwise), $g'' : M'' \rightarrow N''$, $(m, n'') \mapsto n''$, and $\phi' : M'' \rightarrow M$, $(m, n'') \mapsto m$. The diagram is then commutative by diagram chasing and the pullback is exact as $\text{im}(f) = \{(f(l), 0) : l \in L \text{ and } g(f(l)) = \psi(0)\} = \{(m, 0) : m \in M \text{ and } g(m) = \psi(0)\} = \ker(g'')$. Uniqueness: Consider the commutative diagram of short exact sequences,

$$\begin{array}{ccccccccc} \xi'': & 0 & \longrightarrow & M'' & \xrightarrow{(\phi' \ g'')} & M \oplus N'' & \xrightarrow{\begin{pmatrix} g \\ -\psi \end{pmatrix}} & N & \longrightarrow & 0 \\ & & & \downarrow & & \parallel & & \parallel & & \\ \tilde{\xi}'': & 0 & \longrightarrow & \widetilde{M}'' & \longrightarrow & M \oplus N'' & \xrightarrow{\begin{pmatrix} g \\ -\psi \end{pmatrix}} & N & \longrightarrow & 0 \end{array}$$

where M'' and \widetilde{M}'' are from two pullbacks, \mathbf{E}'' and $\widetilde{\mathbf{E}}''$, of \mathbf{E} along ψ . By diagram chasing we can see that there is in fact an isomorphism between M'' and \widetilde{M}'' and so \mathbf{E}'' and $\widetilde{\mathbf{E}}''$ are equivalent as short exact sequences. \square

Example 2.2.27. Consider the short exact sequence,

$$\mathbf{E} : \quad 0 \rightarrow \mathbb{Z} \xrightarrow[nat]{f} \mathbb{Z} \xrightarrow[nat]{g} \frac{\mathbb{Z}}{n\mathbb{Z}} \rightarrow 0,$$

and the \mathbb{Z} -module map $\psi : \mathbb{Z} \rightarrow \mathbb{Z}/n\mathbb{Z}$ is the natural one. Now we can use Proposition 2.2.26 to construct the pullback of \mathbf{E} along ψ .

Firstly, construct the commutative diagram,

$$\begin{array}{ccccccccc}
\mathbf{E}'': & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{f''} & M'' & \xrightarrow{g''} & \mathbb{Z} & \longrightarrow 0 \\
& & & \parallel & & \downarrow \phi' & & \downarrow \psi & \\
\mathbf{E}: & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow[n]{f} & \mathbb{Z} & \xrightarrow[g]{nat} & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow 0
\end{array}$$

and now to find M'' . As both $\psi, g : x \mapsto x + n\mathbb{Z}$, we have,

$$\begin{aligned}
M'' &= \{(x, y) \in \mathbb{Z} \oplus \mathbb{Z} : x + n\mathbb{Z} = y + n\mathbb{Z}\}, \\
&= \{(x, y) \in \mathbb{Z} \oplus \mathbb{Z} : n \mid x - y\}, \\
&\cong \mathbb{Z} \oplus \mathbb{Z}, \text{ by considering the map } (a, b) \mapsto (a, a + nb), \\
&\cong \mathbb{Z}^2,
\end{aligned}$$

and we can set $f'' : \mathbb{Z} \rightarrow M''$, $x \mapsto \overline{(nx, 0)}$, $g'' : M'' \rightarrow \mathbb{Z}$, $\overline{(x, y)} \mapsto y$ and $\phi' : M'' \rightarrow \mathbb{Z}$, $\overline{(x, y)} \mapsto m$. It is clear that this makes the diagram commutative and gives \mathbf{E}'' exact. Hence, the pullback of \mathbf{E} along ψ is,

$$\mathbf{E}'' : 0 \rightarrow \mathbb{Z} \xrightarrow{f''} \mathbb{Z}^2 \xrightarrow{g''} \mathbb{Z} \rightarrow 0,$$

with the maps f'', g'' defined as above.

Now this report will start to consider the results possible by considering exact sequences of

The following theorem is from [1] and the proof that the connecting map exists and is well defined taken from [1] and the proof that the sequence induced by this map is exact from [4]. Both proofs were adapted to use the notation used in this report and some more explanation given when we felt it was necessary.

Theorem 2.2.28. (*Long Exact Sequence*)

Let $0 \rightarrow \mathbf{C} \xrightarrow{f} \mathbf{D} \xrightarrow{g} \mathbf{E} \rightarrow 0$ be a short exact sequence of chain complexes, meaning that f and g are chain maps and for each n the maps

$$0 \rightarrow C_n \xrightarrow{f_n} D_n \xrightarrow{g_n} E_n \rightarrow 0,$$

form a short exact sequence. Then there are connecting maps $c_n : H_n(\mathbf{E}) \rightarrow H_{n-1}(\mathbf{C})$ giving a long exact sequence,

$$\cdots \rightarrow H_{n+1}(\mathbf{E}) \xrightarrow{c_{n+1}} H_n(\mathbf{C}) \xrightarrow{f_*} H_n(\mathbf{D}) \xrightarrow{g_*} H_n(\mathbf{E}) \xrightarrow{c_n} H_{n-1}(\mathbf{C}) \rightarrow \cdots$$

Proof. Have diagram,

$$\begin{array}{ccccccccc}
0 & \longrightarrow & C_{n+1} & \xrightarrow{f_{n+1}} & D_{n+1} & \xrightarrow{g_{n+1}} & E_{n+1} & \longrightarrow & 0 \\
& & \downarrow \gamma_{n+1} & & \downarrow \delta_{n+1} & & \downarrow \epsilon_{n+1} & & \\
0 & \longrightarrow & C_n & \xrightarrow{f_n} & D_n & \xrightarrow{g_n} & E_n & \longrightarrow & 0 \\
& & \downarrow \gamma_n & & \downarrow \delta_n & & \downarrow \epsilon_n & & \\
0 & \longrightarrow & C_{n-1} & \xrightarrow{f_{n-1}} & D_{n-1} & \xrightarrow{g_{n-1}} & E_{n-1} & \longrightarrow & 0
\end{array}$$

- Define the connecting map $c_n : H_n(\mathbf{E}) \rightarrow H_{n-1}(\mathbf{C})$ as follows:
Let \bar{x} be a typical element of $H_n(\mathbf{E})$, with $x \in \ker(\epsilon_n) = Z_n(\mathbf{E})$. Then as g_n is surjective we can lift $x \in E_n$ to some element $y \in D_n$ such that $g_n(y) = x$. From the commutativity of the diagram,

$$g_{n-1}(\delta_n(y)) = \epsilon_n(g_n(y)) = \epsilon_n(x) = 0,$$

since $x \in \ker(\epsilon_n)$. Hence, $\delta_n(y) \in \ker(g_{n-1}) \cong \text{im}(f_{n-1})$. Then as f_{n-1} is injective there exists some $z \in C_{n-1}$ such that $f_{n-1}(z) = \delta_n(y)$. Thus define $c_n(\bar{x}) = \bar{z}$. (Note $z \in \ker(\gamma_{n-1})$ as $\delta_{n-1}(\delta_n(y)) = 0$, then by commutivity $f_{n-2}(\gamma_{n-1}(z)) = 0$ and as f_{n-2} is injective.)

- Not dependent on choice of x or y : Say $y, y' \in D_n$ have images $g_n(y) = x$, $g_n(y') = x'$ where $x, x' \in \ker(\epsilon_n) = Z_n(\mathbf{E})$ with $\bar{x} = \bar{x}'$. Thus $g_n(y) - g_n(y') \in \text{im}(\epsilon_{n+1}) = B_n(\mathbf{E})$. Therefore,

$$\begin{aligned}
g_n(y - y') &= \epsilon_{n+1}(g_{n+1}(u)), \text{ for some } u \in D_{n+1}, \\
&= g_n(\delta_{n+1}(u)).
\end{aligned}$$

Hence, $y - y' - \delta_{n+1}(u) = f_n(v)$ for some $v \in C_n$ by the injectivity of f_n . If $f_{n-1}(z) = \delta_n(y)$ and $f_{n-1}(z') = \delta_n(y')$ then,

$$\begin{aligned}
f_{n-1}(z - z') &= \delta_n(y - y'), \\
&= \delta_n(y - y' - \delta_{n+1}(u)), \text{ as } \delta_n(\delta_{n+1}(u)) = 0 \text{ as chain complex,} \\
&= \delta_n(f_n(v)), \\
&= f_{n-1}(\gamma_n(v)),
\end{aligned}$$

implying $z - z' = \gamma_n(v) \in \text{im}(\gamma_n) = B_{n-1}(\mathbf{C})$. Hence, $\bar{z} = \bar{z}'$ in $H_{n-1}(\mathbf{C})$.

- Exactness at $H_n(\mathbf{C})$: $H_{n+1}(\mathbf{E}) \xrightarrow{c_{n+1}} H_n(\mathbf{C}) \xrightarrow{f_*} H_n(\mathbf{D})$
 $\text{im}(c_{n+1}) \subseteq \ker(f_*)$: We have $f_*(c_{n+1}(\bar{x})) = f_n(z)$ for some $z \in C_n$. But,

$$f_n(z) = \delta_{n+1}g_{n+1}^{-1}(x) \in B_{n+1}(\mathbf{D});$$

that is, $f_*(c_{n+1}(\bar{x})) = 0$.

$\ker(f_*) \subseteq \text{im}(c_{n+1})$: If $f_*(\bar{z}) = \overline{f_n(z)} = \bar{0}$ then $f_n(z) = \delta_{n+1}(y')$ for some $y' \in D_{n+1}$. Since g is a chain map,

$$\begin{aligned}\epsilon_{n+1}(g_{n+1}(y')) &= g_n(\delta_{n+1}(y')), \\ &= g_n(f_n(z)), \\ &= 0, \text{ by exactness of the original sequence,}\end{aligned}$$

and so $g_{n+1}(y') \in Z_n(\mathbf{E})$. However,

$$\begin{aligned}c_{n+1}(\overline{g_{n+1}(y')}) &= \overline{f_n^{-1}(\delta_{n+1}(g_{n+1}^{-1}(g_{n+1}(y'))))}, \\ &= \overline{f_n^{-1}\delta_{n+1}(y')}, \\ &= \overline{f_n^{-1}(f_n(z))}, \\ &= \bar{z}.\end{aligned}$$

- Exactness at $H_n(\mathbf{D})$: $H_n(\mathbf{C}) \xrightarrow{f_*} H_n(\mathbf{D}) \xrightarrow{g_*} H_n(\mathbf{E})$
 $\text{im}(f_*) \subseteq \ker(g_*)$: True as,

$$g_*f_* = (gf)_* = 0_* = 0.$$

$\ker(g_*) \subseteq \text{im}(f_*)$: If $g_*(\bar{y}) = \overline{g_n(y)} = \bar{0}$, then $g_n(y) = \epsilon_{n+1}$ for some $x' \in E_{n+1}$. However, g is surjective meaning $x' = g_{n+1}$ for some $y' \in C_{n+1}$, hence,

$$\begin{aligned}g_n(y) &= \epsilon_{n+1}(g_{n+1}(y')), \\ &= g_n(\delta_{n+1}(y')), \end{aligned}$$

since g is a chain map and so $g_n(y - \delta_{n+1}(y')) = 0$. By exactness, there is $z \in C_n$ with $f_n(z) = y - \delta_{n+1}(y')$. Now $z \in Z_n(\mathbf{C})$ because,

$$\begin{aligned}f_{n-1}(\gamma_n(z)) &= \delta_n(f_n(z)), \\ &= \delta_n(y - \delta_{n+1}(y')), \\ &= \delta_n(y) - \delta_n(\delta_{n+1}(y')), \\ &= 0, \text{ as } y \in Z_n(\mathbf{C}) \text{ and } \delta_n\delta_{n+1} = 0,\end{aligned}$$

then because f_{n-1} is injective, $\gamma_n(z) = 0$. Therefore,

$$\begin{aligned}f_*(\bar{z}) &= \overline{f_n(z)}, \\ &= \overline{y - \delta_{n+1}(y')}, \\ &= \bar{y}.\end{aligned}$$

- Exactness at $H_n(\mathbf{E})$: $H_n(\mathbf{D}) \xrightarrow{g_*} H_n(\mathbf{E}) \xrightarrow{c_n} H_{n-1}(\mathbf{C})$
 $\text{im}(g_*) \subseteq \ker(c_n)$: If $g_*(\bar{y}) = \overline{g_n(y)} \in \text{im}(g_*)$, then $c_n(\overline{g_n(y)}) = \bar{z}$ where,

$$f_{n-1}(z) = \delta_n(g_n^{-1}(g_n(y'))).$$

Since this formula is independent of the choice of lifting of $g_n(y')$, let us choose $g_n^{-1}(g_n(y')) = y'$. Now $\delta_n(g_n^{-1}(g_n(y'))) = \delta_n(y') = 0$ because

$y' \in Z_n(\mathbf{D})$. Thus, $f_{n-1}(z) = 0$ and hence $z = 0$ because f_{n-1} is injective. $\ker(c_n) \subseteq \operatorname{im}(g_*)$: If $c_n(x) = \bar{0}$, then $z' = f_{n-1}^{-1} = f_{n-1}^{-1}(\delta_n(g_n^{-1}(x))) \in B_n(\mathbf{C})$, that is $z' = \gamma_n(z)$ for some $z \in C_n$. However,

$$\begin{aligned} f_{n-1}(z') &= f_{n-1}(\gamma_n(z)), \\ &= \delta_n(f_n(z)), \\ &= \delta_n(g_n^{-1}(x)), \end{aligned}$$

so that $\delta_n(g_n^{-1} - f_n(z)) = 0$, that is $g_n^{-1} - f_n(z) \in \ker(\delta_n)$. Exactness of the original sequence gives $g_n f_n = 0$, so that,

$$\begin{aligned} g_*(\overline{g_n^{-1}(x) - f_n(z)}) &= \overline{g_n(g_n^{-1}(x) - g_n(f_n(z)))}, \\ &= \bar{x}. \end{aligned}$$

□

Note that this report is following Crawley-Boevey's example in [1] by proving the Long Exact Sequence theorem directly and taking the Snake Lemma as a corollary, unlike in other reading material, like [4] where the Long Exact Sequence is given as a corollary of the Snake Lemma. If the reader would like a direct proof of the Snake Lemma, we direct them, as Weibel does in [4], to *It's My Turn* (Rastar-Martin Elford Studios, 1980), where a proof is given in the beginning of the movie.

Corollary 2.2.29. (*Snake Lemma*)

If you have a commutative diagram with exact rows,

$$\begin{array}{ccccccccc} 0 & \longrightarrow & L & \longrightarrow & M & \longrightarrow & N & \longrightarrow & 0 \\ & & \downarrow \theta & & \downarrow \phi & & \downarrow \psi & & \\ 0 & \longrightarrow & L' & \longrightarrow & M' & \longrightarrow & N' & \longrightarrow & 0 \end{array}$$

you get an exact sequence,

$$0 \rightarrow \ker(\theta) \rightarrow \ker(\phi) \rightarrow \ker(\psi) \rightarrow \operatorname{coker}(\theta) \rightarrow \operatorname{coker}(\phi) \rightarrow \operatorname{coker}(\psi) \rightarrow 0$$

Proof. Consider $L \rightarrow L'$, $M \rightarrow M'$ and $N \rightarrow N'$ as chain complexes and use Theorem 2.2.28. □

Remark 2.2.30. A short exact sequence of cochain complexes $0 \rightarrow \mathbf{C} \rightarrow \mathbf{D} \rightarrow \mathbf{E} \rightarrow 0$ gives a long exact sequence,

$$\dots \rightarrow H^{n-1}(\mathbf{E}) \rightarrow H^n(\mathbf{C}) \rightarrow H^n(\mathbf{D}) \rightarrow H^n(\mathbf{E}) \rightarrow H^{n+1}(\mathbf{C}) \rightarrow H^{n+1}(\mathbf{D}) \rightarrow \dots$$

by renumbering in Theorem 2.2.28.

2.3 Homotopy and Quasi-Isomorphism

For this section the report relies heavily on [1], with some added details, such as the definition for null homotopic and the diagram, come from [4] and [3]. However, all examples are original work.

Definition 2.3.1. If $f, g : \mathbf{C} \rightarrow \mathbf{D}$ are chain maps, then f and g are *homotopic*, denoted $f \simeq g$, if for each n there are maps $h_n : C_n \rightarrow D_{n+1}$ such that,

$$f_n - g_n = h_{n-1}\gamma_n + \delta_{n+1}h_n,$$

where the maps are defined ,

$$\begin{array}{ccccccc} \cdots & \longrightarrow & C_{n+1} & \xrightarrow{\gamma_{n+1}} & C_n & \xrightarrow{\gamma_n} & C_{n-1} \xrightarrow{\gamma_{n-1}} \cdots \\ & & \downarrow k_{n+1} & \nearrow h_n & \downarrow k_n & \nearrow h_{n-1} & \downarrow k_{n-1} \\ \cdots & \longrightarrow & D_{n+1} & \xrightarrow{\delta_{n+1}} & D_n & \xrightarrow{\delta_n} & D_{n-1} \xrightarrow{\delta_{n-1}} \cdots \end{array}$$

with k_n representing either f_n or g_n .

A chain map $f : \mathbf{C} \rightarrow \mathbf{D}$ is considered *null-homotopic* if $f \simeq 0$, where 0 is the zero chain map.

Example 2.3.2. Consider the two chain complexes,

$$\mathbf{C} : \quad \cdots \rightarrow 0 \rightarrow \mathbb{Z} \xrightarrow{3} \mathbb{Z} \rightarrow 0 \rightarrow \cdots \quad \& \quad \mathbf{D} : \quad \cdots \rightarrow \frac{\mathbb{Z}}{9\mathbb{Z}} \xrightarrow{3} \frac{\mathbb{Z}}{9\mathbb{Z}} \xrightarrow{3} \frac{\mathbb{Z}}{9\mathbb{Z}} \rightarrow \cdots,$$

such that $C_1, C_0 = \mathbb{Z}$ and $D_n = \mathbb{Z}/9\mathbb{Z}$. Then the two chain maps $f, g : \mathbf{C} \rightarrow \mathbf{D}$, where $f_0, f_1 : x \mapsto 4x + 9\mathbb{Z}$ and $g_0, g_1 : x \mapsto x + 9\mathbb{Z}$ are homotopic where $h_0 : \mathbb{Z} \rightarrow \mathbb{Z}/9\mathbb{Z}, x \mapsto x + 9\mathbb{Z}$ and $h_1 : \mathbb{Z} \rightarrow \mathbb{Z}/9\mathbb{Z}, x \mapsto 3x + 9\mathbb{Z}$.

Proposition 2.3.3. If $f, g : \mathbf{C} \rightarrow \mathbf{D}$ are homotopic then for each n they induce exactly the same map $H_n(\mathbf{C}) \rightarrow H_n(\mathbf{D})$.

Proof. Let $\bar{x} \in H_n(\mathbf{C})$ such that $x \in Z_n(\mathbf{C})$. Then,

$$\begin{aligned} H_n(f)(\bar{x}) - H_n(g)(\bar{x}) &= \overline{f_n(x)} - \overline{g_n(x)}, \\ &= \overline{h_{n-1}\gamma_n(x) - \delta_{n+1}h_n(x)}, \\ &= \overline{\delta_{n+1}h_n(x)}, \text{ as } x \in Z_n(\mathbf{C}) = \ker(\gamma_n), \\ &= 0, \text{ as } \delta_{n+1}h_n(x) \in B_n(\mathbf{D}) = \text{im}(\delta_{n+1}). \end{aligned}$$

□

Proposition 2.3.4. If $f, g : \mathbf{C} \rightarrow \mathbf{D}$ are homotopic and N is an R -module, then the induced cochain maps $\text{Hom}(\mathbf{D}, N) \rightarrow \text{Hom}(\mathbf{C}, N)$ are homotopic.

Proof. A homotopy is given by maps $h_n : C_n \rightarrow D_{n+1}$ such that,

$$f_n - g_n = h_{n-1}\gamma_n + \delta_{n+1}h_n.$$

Let $h^n : \text{Hom}(\mathbf{D}, N)^n \rightarrow \text{Hom}(\mathbf{C}, N)^{n-1}$ be $\text{Hom}(h_{n-1}, N)$, as $\text{Hom}(D, N)^n \cong \text{Hom}(D_n, N)$ and $\text{Hom}(C, N)^{n-1} \cong \text{Hom}(C_{n-1}, N)$. □

Definition 2.3.5. A chain map $f : \mathbf{C} \rightarrow \mathbf{D}$ is a *homotopy equivalence* if there is a chain map $g : \mathbf{D} \rightarrow \mathbf{C}$ such that gf and fg are homotopic to the respective identity maps of \mathbf{C} and \mathbf{D} .

If there exists a homotopy equivalence, $f : \mathbf{C} \rightarrow \mathbf{D}$, \mathbf{C} and \mathbf{D} are said to be *homotopy equivalent*.

Remark 2.3.6. The reader is advised not to confuse these definitions: Note that the two chain maps $f, g : \mathbf{C} \rightarrow \mathbf{D}$ can be homotopic, whilst two chain complexes \mathbf{C}, \mathbf{D} can be homotopy equivalent.

Proposition 2.3.7. A homotopy equivalence $f : \mathbf{C} \rightarrow \mathbf{D}$ of chain complexes induces a homotopy equivalence of cochain complexes $\text{Hom}(\mathbf{D}, N) \rightarrow \text{Hom}(\mathbf{C}, N)$. In particular, $H^n(\mathbf{D}, N) \cong H^n(\mathbf{C}, N)$.

Proof. Omitted. □

Definition 2.3.8. A chain map $f : \mathbf{C} \rightarrow \mathbf{D}$ is a *quasi-isomorphism* if for each n the map $H_n(\mathbf{C}) \rightarrow H_n(\mathbf{D})$ is an isomorphism.

Proposition 2.3.9. If $f : \mathbf{C} \rightarrow \mathbf{D}$ is a homotopy equivalence then it is a quasi-isomorphism.

Proof. Assume that $f : \mathbf{C} \rightarrow \mathbf{D}$ is a homotopy equivalence, then there exists some chain map $g : \mathbf{D} \rightarrow \mathbf{C}$ such that $fg \simeq id_{\mathbf{D}}$ and $gf \simeq id_{\mathbf{C}}$. By Proposition 2.3.3, since $fg \simeq id_{\mathbf{D}}$ then they both induce the same map $H_n(\mathbf{D}) \rightarrow H_n(\mathbf{D})$ and similarly gf and $id_{\mathbf{C}}$ induce the same map $H_n(\mathbf{C}) \rightarrow H_n(\mathbf{C})$. Hence, f induces an isomorphism $H_n(\mathbf{C}) \rightarrow H_n(\mathbf{D})$ as it has an inverse and so is a quasi-isomorphism. □

Example 2.3.10. This example shows that the converse to Proposition 2.3.9 is not true. Consider the chain complexes,

$$\begin{array}{ccccccc}
 \mathbf{C} & \cdots & \longrightarrow & 0 & \xrightarrow{H_1=0} & \mathbb{Z} & \xrightarrow{H_0=\frac{\mathbb{Z}}{2\mathbb{Z}}, 2} & \mathbb{Z} & \xrightarrow{\quad} & 0 & \longrightarrow & \cdots \\
 & & & \downarrow & & \downarrow & & \downarrow \text{nat} & & \downarrow & & \\
 \mathbf{D} & \cdots & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & \frac{\mathbb{Z}}{2\mathbb{Z}} & \longrightarrow & 0 & \longrightarrow & \cdots \\
 & & & & & & & H_0=\frac{\mathbb{Z}}{2\mathbb{Z}} & & & &
 \end{array}$$

and so $H_0(\mathbf{C}) = \frac{\mathbb{Z}}{2\mathbb{Z}} = H_0(\mathbf{D})$ and so f is a quasi-isomorphism. However, it is not a homotopy equivalence.

Definition 2.3.11. A chain complex \mathbf{C} is *contractible* if it is homotopy equivalent to the zero complex.

Equivalent condition: $id_{\mathbf{C}}$ is homotopic to $0_{\mathbf{C}}$.

Equivalent condition: There are maps $h_n : C_n \rightarrow C_{n+1}$ with,

$$id_{C_n} = h_{n-1}\gamma_n + \delta_{n+1}h_n, \text{ for all } n.$$

This is called a *contracting homotopy*.

Theorem 2.3.12. *A chain complex \mathbf{C} is contractible if and only if it is acyclic and all of the short exact sequences,*

$$0 \rightarrow Z(\mathbf{C}) \xrightarrow{\iota_n} C_n \xrightarrow{\gamma_n} B_{n-1}(\mathbf{C}) \rightarrow 0,$$

are split, where ι_n is the inclusion.

Proof. \Rightarrow : If \mathbf{C} is contractible then it is quasi-isomorphic to the zero complex, so acyclic by Proposition 2.3.9. Let h be the contracting homotopy. Let $s : B_{n-1}(\mathbf{C}) \rightarrow C_n$ be the restriction of $h_{n-2} : C_{n-1} \rightarrow C_n$. If $x \in B_{n-1}(\mathbf{C}) = \text{im}(\gamma_n)$,

$$\begin{aligned} B_{n-1}(\mathbf{C}) \ni x &= id_{C_{n-1}}(x), \\ &= (h_{n-1}\gamma_{n-1} + \gamma_n h_{n-1})(x), \\ &= h_{n-2}(\gamma_{n-1}(x)) + \gamma_n(h_{n-1}(x)), \\ &= \gamma_n(h_{n-1}(x)), \\ &= \gamma_n(s(x)). \end{aligned}$$

Thus s makes γ_n is a retraction in the short exact sequence. \Leftarrow : Now suppose that \mathbf{C} is acyclic and all the exact sequences are split. Then for all n there are sections,

$$s_{n-1} : B_{n-1}(\mathbf{C}) \rightarrow C_n.$$

If $x \in C_n$ then $x - s_{n-1}\gamma_n x \in Z_n(\mathbf{C}) = B_n(\mathbf{C})$ so we can define a function $h_n : C_n \rightarrow C_{n-1}$ by,

$$h_n(x) = s_n(x - s_{n-1}\gamma_n x).$$

Then,

$$\begin{aligned} (h_{n-1}\gamma_n + \gamma_{n+1}h_n)(x) &= s_{n-1}(\gamma_n x - s_{n-2}\gamma_{n-1}\gamma_n x) + \gamma_{n+1}s_n(x - s_{n-1}\gamma_n x), \\ &= s_{n-1}\gamma_n x + (x - s_{n-1}\gamma_n x), \text{ as } s_n \text{ is a section,} \\ &= x. \end{aligned}$$

□

2.4 Projective and Injective Resolutions

In this section we look at projective and injective modules and resolutions, for this the reader will need some prior knowledge of free modules, which will not be covered in this report. The reader is advised to look at [5], [4] and [3] for more information regarding free modules.

The following properties for projective modules come from [1] with added details from either my own work or [3]. In order to have a clear definition of a projective modules, rather than as a culmination of properties, we have promoted the first property from [1] to a definition and to aid this we give a separate definition for a lifting as in [3].

Definition 2.4.1. Suppose we have a map $g : M \rightarrow N$ then a *lifting* of a map $p : A \rightarrow N$ is a map $q : A \rightarrow M$ with $gq = p$, i.e. the following diagram

commutes.

$$\begin{array}{ccc}
 & A & \\
 q \swarrow & & \searrow p \\
 M & \xrightarrow{g} & N
 \end{array}$$

Definition 2.4.2. A module P is *projective* if, whenever $g : M \rightarrow N$ is surjective and $p : P \rightarrow N$ is any map, there exists a lifting $q : P \rightarrow M$ making the following diagram commutes:

$$\begin{array}{ccc}
 & P & \\
 \exists q \swarrow & & \searrow p \\
 M & \xrightarrow{g} & N
 \end{array}$$

Proposition 2.4.3. *The following for a module P are equivalent:*

- (i) P is projective.
- (ii) The sequence $0 \rightarrow \text{Hom}(P, L) \rightarrow \text{Hom}(P, M) \rightarrow \text{Hom}(P, N) \rightarrow 0$ is exact for any short exact sequence $0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$.
- (iii) Any short exact sequence $0 \rightarrow L \rightarrow M \rightarrow P \rightarrow 0$ splits.
- (iv) P is isomorphic to a direct summand of free modules.

Proof. (i) \Rightarrow (ii): As P is projective we have that,

$$\begin{array}{ccccccc}
 & & & & P & & \\
 & & & & \exists q \swarrow & & \searrow p \\
 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & N \longrightarrow 0
 \end{array}$$

Hence, we have $q \in \text{Hom}(P, M)$ such that $gq = p \in \text{Hom}(P, N)$ which can also be written $p = gq = g_*(q) \in \text{im}(g_*)$, defining a surjective map, $g_* : \text{Hom}(P, M) \rightarrow \text{Hom}(P, N)$. Thus,

$$0 \rightarrow \text{Hom}(P, L) \rightarrow \text{Hom}(P, M) \xrightarrow{g_*} \text{Hom}(P, N) \rightarrow 0$$

is exact by Proposition 2.2.10.

(ii) \Rightarrow (iii): By assumption, if we have the short exact sequence $0 \rightarrow L \rightarrow M \rightarrow P \rightarrow 0$ then we have an exact sequence,

$$0 \rightarrow \text{Hom}(P, L) \rightarrow \text{Hom}(P, M) \rightarrow \text{Hom}(P, P) \rightarrow 0.$$

Then we can lift the identity map $id_P \in Hom(P, P)$ to some $q \in Hom(P, M)$, such that:

$$\begin{array}{ccc} & & P \\ & \swarrow \exists q & \downarrow p \\ M & \xrightarrow{g} & P \end{array}$$

Thus $g : M \rightarrow P$ is a retraction as we have $q : P \rightarrow M$ such that $gq = id_P$. Hence, $0 \rightarrow L \rightarrow M \rightarrow P \rightarrow 0$ splits by Lemma 2.2.16.

(iii) \Rightarrow (iv): By choosing a generating set of P we get a surjection from a free module F onto P , $g : F \rightarrow P$, and this gives the short exact sequence,

$$0 \rightarrow \ker(g) \rightarrow F \xrightarrow{g} P \rightarrow 0,$$

and this splits by assumption. Hence, $F \cong \ker(g) \oplus P$ and so P is a direct summand of F by Corollary 2.2.18.

(iv) \Rightarrow (i): By assumption, P is a direct summand of F and so there are maps $r : F \rightarrow P$ and $s : P \rightarrow F$ with $rs = id_P$. Now consider the diagram,

$$\begin{array}{ccc} F & \xrightleftharpoons[s]{r} & P \\ \downarrow \exists t & & \downarrow p \\ M & \xrightarrow{g} & N \end{array}$$

where g is surjective. The composite map $pr : F \rightarrow N$; since F is free, it is surjective, and so there is a map $t : F \rightarrow M$ with $gt = pr$. Define $q : P \rightarrow M$ by $q = ts$ and then we can see that $gq = p$ as,

$$gq = gts = prs = pid_P = p.$$

Hence P is projective. □

Now we have established some properties of projective modules we can prove a corollary of the Long Exact Sequence Theorem in [1].

Corollary 2.4.4. (*Corollary to Theorem 2.2.28*)

If \mathbf{P} is a chain complex of projective R -modules and $0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ is a short exact sequence of R -modules then you get a long exact sequence in cohomology.

$$\dots \rightarrow H^{n-1}(\mathbf{P}, N) \rightarrow H^n(\mathbf{P}, L) \rightarrow H^n(\mathbf{P}, M) \rightarrow H^n(\mathbf{P}, N) \rightarrow H^{n+1}(\mathbf{P}, L) \rightarrow \dots$$

Proof. Since P_n is projective for every n , Proposition 2.4.3, tells us we get an exact sequence,

$$0 \rightarrow Hom(P_n, L) \rightarrow Hom(P_n, M) \rightarrow Hom(P_n, N) \rightarrow 0.$$

Then use Remark 2.2.30. □

As with projective modules we will use the first property given in [1] to define injective modules, and then provide the properties as in [1] with some details from [3].

Definition 2.4.5. A module I is *injective* if, whenever $f : L \rightarrow M$ is an injection, there exists a map $j : M \rightarrow I$ which extends any map $i : L \rightarrow I$, making the following diagram commute.

$$\begin{array}{ccc} & I & \\ & \uparrow i & \nwarrow j \\ L & \xrightarrow{g} & M \end{array}$$

Proposition 2.4.6. *The following properties of a module I are equivalent:*

- (i) I is injective.
- (ii) The sequence $0 \rightarrow \text{Hom}(N, I) \rightarrow \text{Hom}(M, I) \rightarrow \text{Hom}(L, I) \rightarrow 0$ is exact for any short exact sequence $0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$.
- (iii) Any short exact sequence $0 \rightarrow I \rightarrow M \rightarrow N \rightarrow 0$ splits.

Proof. (i) \Rightarrow (ii) \Rightarrow (iii): Dual to Proposition 2.4.3 for projectives. (iii) \Rightarrow (i): Consider the $0 \rightarrow L \rightarrow M \rightarrow M/L \rightarrow 0$ and construct its pushout along $\theta : L \rightarrow I$:

$$\begin{array}{ccccccc} 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & \frac{M}{L} \longrightarrow 0 \\ & & \downarrow \theta & & \downarrow \phi & & \parallel \\ 0 & \longrightarrow & I & \xrightarrow{h} & M' & \longrightarrow & \frac{M}{L} \longrightarrow 0 \\ & & & \nwarrow \exists r & & & \end{array}$$

By assumption $0 \rightarrow I \rightarrow M' \rightarrow M/L \rightarrow 0$ splits and so $h : I \rightarrow M'$ has a retraction $r : M' \rightarrow I$. Then,

$$r\phi f = rh\theta = \theta,$$

so $r\phi : M \rightarrow I$ extends $\theta : L \rightarrow I$. Hence I is injective. \square

Definition 2.4.7. If M is an R -module, then a *projective resolution* of M is an exact sequence,

$$\mathbf{P} : \quad \dots \rightarrow P_2 \xrightarrow{d_2} P_1 \xrightarrow{d_1} P_0 \xrightarrow{\epsilon} M \rightarrow 0$$

where each P_i is a projective module.

Proposition 2.4.8. *A projective resolution \mathbf{P} of M is equivalent to giving a non-negative chain complex \mathbf{P}_\bullet of projective modules and a quasi-isomorphism $f : \mathbf{P}_\bullet \rightarrow \mathbf{M}$, where all the f_n are trivial apart from $f_0 : P_0 \rightarrow M$.*

Proof. Consider the diagram,

$$\begin{array}{ccccccccc}
 \cdots & \longrightarrow & P_2 & \longrightarrow & P_1 & \longrightarrow & P_0 & \longrightarrow & 0 & \longrightarrow & \cdots \\
 & & \downarrow & & \downarrow & & \downarrow f_0 & & \downarrow & & \\
 \cdots & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & M & \longrightarrow & 0 & \longrightarrow & \cdots
 \end{array}$$

letting $f_0 : P_0 \twoheadrightarrow M$ be any surjection and setting $\theta : P_1 \twoheadrightarrow \ker(f_0)$, $\phi : P_2 \twoheadrightarrow \ker(\theta)$, etc, as surjections. Then we have $H_n(\mathbf{P}_\bullet) = 0 = H_n(\mathbf{M})$ for all $n \geq 1$. At $n = 0$ we have $H_0(\mathbf{P}_\bullet) = P_0/\ker(f_0)$ and $H_0(\mathbf{M}) = M$, but as f_0 is a surjection, the first isomorphism theorem gives $M \cong P_0/\ker(f_0)$ and hence $H_n(\mathbf{P}_\bullet) \cong H_n(\mathbf{M})$ for all n and so $f : \mathbf{P}_\bullet \rightarrow \mathbf{M}$ is a quasi-isomorphism. \square

Example 2.4.9. Let $M = \mathbb{Z}/n\mathbb{Z}$ be considered as a \mathbb{Z} -module. Then it has a projective resolution,

$$\cdots \rightarrow 0 \rightarrow \mathbb{Z} \xrightarrow{n} \mathbb{Z} \rightarrow \frac{\mathbb{Z}}{n\mathbb{Z}} \rightarrow 0.$$

Also, we can see that there is a quasi-isomorphism $f : \mathbf{P}_\bullet \rightarrow \mathbf{M}$,

$$\begin{array}{ccccccccc}
 \cdots & \longrightarrow & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{n} & \mathbb{Z} & \longrightarrow & 0 & \longrightarrow & \cdots \\
 & & \downarrow & & \downarrow & & \downarrow nat & & \downarrow & & \\
 \cdots & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & \frac{\mathbb{Z}}{n\mathbb{Z}} & \longrightarrow & 0 & \longrightarrow & \cdots
 \end{array}$$

since the homologies are isomorphic at every n .

Definition 2.4.10. Given a projective resolution \mathbf{P} of M ,

$$\mathbf{P} : \cdots \rightarrow P_n \xrightarrow{d_n} P_{n-1} \rightarrow \cdots \rightarrow P_1 \xrightarrow{d_1} P_0 \xrightarrow{\epsilon} M \rightarrow 0,$$

the *syzygies* of M are the modules $\Omega^n M = \text{im}(d_n : P_n \rightarrow P_{n-1})$ and $\Omega^0 M = M$.

Note that here we used Crawley-Boevey's notation for the syzygies from [1] rather than Rotman's in [3]. However, they are clearly the same definition as exactness of the projective resolution gives,

$$K_n = \ker(d_n : P_n \rightarrow P_{n-1}) = \text{im}(d_{n+1} : P_{n+1} \rightarrow P_n) = \Omega^{n+1} M,$$

and as the following remark demonstrates it is useful to recall this result:

Lemma 2.4.11. *Definition 2.4.10 implies that there are exact sequences,*

$$0 \rightarrow \Omega^{n+1} M \rightarrow P_n \rightarrow \Omega^n M \rightarrow 0.$$

Proof. Note that $\Omega^{n+1} M = \text{im}(d_{n+1} : P_{n+1} \rightarrow P_n) = \ker(d_n : P_n \rightarrow P_{n-1})$ and $\Omega^n M = \text{im}(d_n : P_n \rightarrow P_{n-1})$. \square

Definition 2.4.12. If M is an R -module, then an *injective resolution* of M is an exact sequence,

$$\mathbf{I}: \quad 0 \rightarrow M \xrightarrow{\eta} I^0 \xrightarrow{d^0} I^1 \xrightarrow{d^1} I^2 \rightarrow \dots,$$

where each I^i is an injective module.

Since the definition for a cosyzygy is not given in [1] we turn to [3] for the following definition.

Definition 2.4.13. Given an injective resolution,

$$\mathbf{I}: \quad 0 \rightarrow M \xrightarrow{\eta} I^0 \xrightarrow{d^0} I^1 \rightarrow \dots \rightarrow I^n \xrightarrow{d^n} I^{n+1} \rightarrow \dots$$

the *cosyzygies* of M are the modules $\mathcal{U}^n = \text{coker}(d^{n-1})$, for $n \geq 1$ and with $\mathcal{U}^0 M = \text{coker}(\eta)$.

Theorem 2.4.14. (*Comparison Theorem*)

Any map of modules $f : M \rightarrow M'$ can be lifted to a map of projective resolutions.

$$\begin{array}{ccccccccc} \dots & \longrightarrow & P_2 & \xrightarrow{d_2} & P_1 & \xrightarrow{d_1} & P_0 & \xrightarrow{\epsilon} & M & \longrightarrow & 0 \\ & & \downarrow \hat{f}_2 & & \downarrow \hat{f}_1 & & \downarrow \hat{f}_0 & & \downarrow f & & \\ \dots & \longrightarrow & P'_2 & \xrightarrow{d'_2} & P'_1 & \xrightarrow{d'_1} & P'_0 & \xrightarrow{\epsilon'} & M' & \longrightarrow & 0 \end{array}$$

Moreover, any two such lifts are homotopic as chain maps $\mathbf{P} \rightarrow \mathbf{P}'$.

Proof. Firstly, we show the existence of the lift. Consider the diagram:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \Omega^1 M & \longrightarrow & P_0 & \longrightarrow & M \longrightarrow 0 \\ & & \downarrow \Omega^1 f & & \downarrow \hat{f}_0 & & \downarrow f \\ 0 & \longrightarrow & \Omega^1 M' & \longrightarrow & P'_0 & \longrightarrow & M' \longrightarrow 0 \end{array} \quad (2.1)$$

Now as these are exact sequences by Lemma 2.4.11, the map $\epsilon' : P'_0 \rightarrow M'$ is surjective. Then since P_0 is projective we can lift the composite map $f\epsilon : P_0 \rightarrow M'$,

$$\begin{array}{ccc} & P_0 & \\ \hat{f}_0 \swarrow & \downarrow f\epsilon & \\ P'_0 & \xrightarrow{\epsilon'} & M' \end{array}$$

and so have a map \hat{f}_0 making the right hand square of 2.1 commute. Then by diagram chasing there is a map $\Omega^1 f$ making the left hand square of 2.1 commute.

The same argument gets \hat{f}_1 and $\Omega^2 f$.

$$\begin{array}{ccccccc}
0 & \longrightarrow & \Omega^2 M & \longrightarrow & P_1 & \longrightarrow & \Omega^1 M \longrightarrow 0 \\
& & \downarrow \Omega^2 f & & \downarrow \hat{f}_1 & & \downarrow \Omega^1 f \\
0 & \longrightarrow & \Omega^2 M' & \longrightarrow & P'_1 & \longrightarrow & \Omega^1 M' \longrightarrow 0
\end{array}$$

etc.

Finally, to show that any two lifts are homotopic it is equivalent to show that any lift of the zero map $M \rightarrow M'$ is homotopic to zero. Now,

$$\begin{array}{ccccccccccc}
\cdots & \longrightarrow & P_2 & \xrightarrow{d_2} & P_1 & \xrightarrow{d_1} & P_0 & \xrightarrow{\epsilon} & M & \longrightarrow & 0 \\
& & \downarrow \hat{f}_2 & & \downarrow \hat{f}_1 & & \downarrow \hat{f}_0 & & \downarrow 0 & & \\
\cdots & \longrightarrow & P'_2 & \xrightarrow{d'_2} & P'_1 & \xrightarrow{d'_1} & P'_0 & \xrightarrow{\epsilon'} & M' & \longrightarrow & 0
\end{array}$$

Then $\epsilon \hat{f}_0 = 0$ by commutativity, and so \hat{f}_0 has an image contained in $\Omega^1 M'$. Now $d'_1 : P'_1 \twoheadrightarrow \Omega^1 M'$ is surjective and P_0 is projective so \hat{f}_0 lifts to a map $h_0 : P_0 \rightarrow P'_1$.

$$\begin{array}{ccc}
& P_0 & \\
h_0 \swarrow & \downarrow \hat{f}_0 & \\
P_1 & \twoheadrightarrow & \Omega^1 M'
\end{array}$$

Thus $\hat{f}_0 = d'_1 h_0$.

Now suppose we have constructed h_0, h_1, \dots, h_{n-1} with,

$$\hat{f}_i = d_{i+1} h_i + h_{i-1} d_i, \text{ for } 0 < i < n.$$

Then,

$$\begin{aligned}
d'_n(\hat{f}_n - h_{n-1} d_n) &= d'_n \hat{f}_n - d'_n h_{n-1} d_n, \\
&= \hat{f}_{n-1} d_n - d'_n h_{n-1} d_n, \quad (d'_n \hat{f}_n = \hat{f}_{n-1} d_n) \text{ by commutativity,} \\
&= (\hat{f}_{n-1} - d'_n h_{n-1}) d_n.
\end{aligned}$$

If $n = 1$ then $(\hat{f}_0 - d'_1 h_0) d_1 = 0$ and if $n > 1$ $(\hat{f}_{n-1} - d'_n h_{n-1}) d_n = (\hat{f}_{n-1} - h_{n-2} d_{n-1}) d_n$, so also zero. Thus $\hat{f}_n - h_{n-1} d_n$ has image contained in $\Omega^{n+1} M'$. Thus it lifts to a map $h_n : P_n \rightarrow P'_{n+1}$. \square

Corollary 2.4.15. *If \mathbf{P} and \mathbf{P}' are projective resolutions of M then there is a homotopy equivalence $f : \mathbf{P} \rightarrow \mathbf{P}'$ such that the triangle,*

$$\begin{array}{ccc}
\mathbf{P} & & \\
\downarrow & \searrow f & \\
\mathbf{P}' & \longrightarrow & M(\text{in deg } 0)
\end{array}$$

commutes. Moreover, f is unique up to homotopy.

Proof. The identity map $id_M : M \rightarrow M$ lifts to chain maps $f : \mathbf{P} \rightarrow \mathbf{P}'$ and $g : \mathbf{P}' \rightarrow \mathbf{P}$. Now $gf : \mathbf{P} \rightarrow \mathbf{P}$ is a lift of the identity map id_M , so it is homotopic to $id_{\mathbf{P}}$. Similarly, $fg : \mathbf{P}' \rightarrow \mathbf{P}'$ is homotopic to $id_{\mathbf{P}'}$.

The uniqueness of f up to homotopy is part of the Comparison Theorem (Thm 2.4.14). \square

This last part of the section gives a small introduction to projective covers which will be used to define the Auslander-Reiten translate in Chapter 4.

Definition 2.4.16. A submodule N of a module M is *superfluous* if, whenever $L \subseteq M$ is a submodule with $L + N = M$, then $L = M$.

Definition 2.4.17. A *projective cover* of a module M is an ordered pair (P, ϵ) where P is projective and $\epsilon : P \rightarrow M$ is a surjective map with $\ker \epsilon$ a superfluous submodule of P .

Lemma 2.4.18. Let (P, ϵ) be a projective cover of a module M . If P' is projective and $\psi : P' \rightarrow M$ is surjective, then any lifting $\phi : P' \rightarrow P$ is surjective.

$$\begin{array}{ccc} & P' & \\ & \swarrow \phi & \downarrow \psi \\ P & \xrightarrow{\epsilon} & M \end{array}$$

Proof. See [3] \square

Remark 2.4.19. In [11] we have the results that if A is a finite dimensional k -algebra, then for each left module M there exists projective cover. Furthermore, if (P, ϵ) and (P', ϵ') are projective covers of M then $P \cong P'$.

2.5 Ext

The following section contains theory on the right-derived functor Ext , however, in an effort to steer clear of category theory, this report will define Ext as Crawley-Boevey does in [1]. If the reader is interested in exploring category theory and Ext as a functor they are directed to start with Appendix A of [4] which introduces category theory language and then look at the derived functors sections in both [4] and [3]. This section will follow [1] closely as it explores Ext theory without the need of category theory, with some additional results from [4]. As such, the reader is advised that, unless otherwise stated, the results of this section come from [1], with only minor details added where it is felt they aid the reader's understanding.

Definition 2.5.1. If M and N are R -modules then $Ext^n(M, N)$, or more precisely $Ext_R^n(M, N)$, is defined as follows:

- Choose a projective resolution \mathbf{P} of M .
- Set $Ext^n(M, N) = H^n(\mathbf{P}, N)$.

Thus if,

$$\dots \rightarrow P_2 \rightarrow P_1 \rightarrow P_0 \rightarrow M \rightarrow 0,$$

is the projective resolution, then $Ext^n(M, N)$ is the cohomology in degree n of the cochain complex,

$$0 \rightarrow Hom(P_0, N) \rightarrow Hom(P_1, N) \rightarrow Hom(P_2, N) \rightarrow \dots$$

Remark 2.5.2. Note that this definition does not depend on the choice of projective resolution. If \mathbf{P}' is another projective resolution there is a homotopy equivalence $f : \mathbf{P} \rightarrow \mathbf{P}'$ by Corollary 2.4.15. This gives a homotopy equivalence of cochain complexes $f^* : Hom(\mathbf{P}', N) \rightarrow Hom(\mathbf{P}, N)$. Proposition 2.3.9 says this is a quasi-isomorphism and so induces isomorphisms on the cohomology $H^n(\mathbf{P}', N) \rightarrow H^n(\mathbf{P}, N)$. Moreover, the homotopy equivalence f is unique up to homotopy, so the cochain map is unique up to homotopy. Thus the map $H^n(\mathbf{P}', N) \rightarrow H^n(\mathbf{P}, N)$ is uniquely determined.

Proposition 2.5.3. (i) *If $\theta : N \rightarrow N'$ is a map there is a natural map $Ext^n(M, N) \rightarrow Ext^n(M, N')$.*

(ii) *If $\phi : M'' \rightarrow M$ is a map there is a natural map $Ext^n(M, N) \rightarrow Ext^n(M'', N)$.*

Proof. (i) As \mathbf{P} is a projective resolution of M , $\theta : N \rightarrow N'$ induces a chain map $Hom(\mathbf{P}, N) \rightarrow Hom(\mathbf{P}, N')$.

(ii) $\phi : M'' \rightarrow M$ lifts to a chain map $\mathbf{P}'' \rightarrow \mathbf{P}$ of projective resolutions unique up to homotopy (Thm 2.4.14) and so induces a cochain map $Hom(\mathbf{P}, N) \rightarrow Hom(\mathbf{P}'', N)$ unique up to homotopy, giving unique maps on Ext^n . □

Proposition 2.5.4. (i) $Ext^n(M, N \oplus N') \cong Ext^n(M, N) \oplus Ext^n(M, N')$.

(ii) $Ext^n(M \oplus M', N) \cong Ext^n(M, N) \oplus Ext^n(M', N)$.

Proof. (i) If \mathbf{P} is a projective resolution of M then $Hom(\mathbf{P}, N \oplus N') \cong Hom(\mathbf{P}, N) \oplus Hom(\mathbf{P}, N')$.

(ii) If \mathbf{P}' is a projective resolution of M' then $\mathbf{P} \oplus \mathbf{P}'$ is a projective resolution of $M \oplus M'$ and $Hom(\mathbf{P} \oplus \mathbf{P}', N) \cong Hom(\mathbf{P}, N) \oplus Hom(\mathbf{P}', N)$. □

Lemma 2.5.5.

$$Ext^n(M, N) \cong \begin{cases} 0 & n < 0, \\ Hom(M, N) & n = 0, \\ coker(Hom(P_{n-1}, N) \xrightarrow{\iota_{n-1}^*} Hom(\Omega^n M, N)) & n > 0, \end{cases}$$

where $0 \rightarrow \Omega^n M \xrightarrow{\iota_n} P_{n-1} \rightarrow \Omega^{n-1} M \rightarrow 0$.

Proof. $n < 0$: The claim is clear as $\text{Hom}(\mathbf{P}, N)$ is a non-negative cochain complex.

$n \geq 0$: By definition,

$$\text{Ext}^n(M, N) = H^n(\mathbf{P}, N) = \frac{\ker(d_{n+1}^* : \text{Hom}(P_n, N) \rightarrow \text{Hom}(P_{n+1}, N))}{\text{im}(d_n^* : \text{Hom}(P_{n-1}, N) \rightarrow \text{Hom}(P_n, N))}.$$

Thus,

$$\begin{aligned} \text{Ext}^n(M, N) &= \frac{\ker(d_{n+1}^* : \text{Hom}(P_n, N) \rightarrow \text{Hom}(P_{n+1}, N))}{\text{im}(d_n^* : \text{Hom}(P_{n-1}, N) \rightarrow \text{Hom}(P_n, N))}, \\ &\cong \frac{\text{codomain}(\gamma : \text{Hom}(P_{n-1}, N) \rightarrow \ker(d_{n+1}^*))}{\text{im}(\gamma : \text{Hom}(P_{n-1}, N) \rightarrow \ker(d_{n+1}^*))}, \\ &\cong \text{coker}(\gamma : \text{Hom}(\text{Hom}(P_{n-1}, N) \rightarrow \ker(d_{n+1}^*))). \end{aligned}$$

Now there is an exact sequence,

$$P_{n+1} \xrightarrow{d_{n+1}} P_n \xrightarrow{d_n} \Omega^n M \rightarrow 0,$$

which then induces the exact sequence,

$$0 \rightarrow \text{Hom}(\Omega^n M, N) \rightarrow \text{Hom}(P_n, N) \xrightarrow{d_{n+1}^*} \text{Hom}(P_{n+1}, N),$$

and so, $\ker(d_{n+1}^*) \cong \text{im}(\text{Hom}(\Omega^n M, N) \rightarrow \text{Hom}(P_n, N)) \cong \text{Hom}(\Omega^n M, N)$.

Note that if we let $P_{-1} = 0$ and $\iota_0 : M \rightarrow 0$ then at $n = 0$ we have,

$$\begin{aligned} \text{coker}(\text{Hom}(P_{-1}, N) \xrightarrow{\iota_0^*} \text{Hom}(\Omega^0 M, N)) &= \text{coker}(\text{Hom}(0, N) \xrightarrow{\iota_0^*} \text{Hom}(M, N)), \\ &\cong \text{Hom}(M, N). \end{aligned}$$

□

Proposition 2.5.6. *If X is a module then for any short exact sequence $0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ you get a long exact sequence,*

$$\begin{aligned} 0 \rightarrow \text{Hom}(X, L) \rightarrow \text{Hom}(X, M) \rightarrow \text{Hom}(X, N) \rightarrow \\ \rightarrow \text{Ext}^1(X, L) \rightarrow \text{Ext}^1(X, M) \rightarrow \text{Ext}^1(X, N) \rightarrow \\ \rightarrow \text{Ext}^2(X, L) \rightarrow \dots \end{aligned}$$

It is called the long exact sequence for $\text{Hom}(X, -)$.

Proof. This is the long exact sequence in cohomology for the chain complex \mathbf{P} , a projective resolution of X . (Corollary ??). □

Lemma 2.5.7. *$\text{Ext}^n(M, N) = 0$ for $n > 0$ if either:*

- (i) M is projective, or,
- (ii) N is injective.

Proof. (i) If M is projective you can use the projective resolution,

$$\dots \rightarrow 0 \rightarrow 0 \rightarrow M \rightarrow M \rightarrow 0.$$

(ii) If N is injective then the exact sequence,

$$0 \rightarrow \Omega^n M \xrightarrow{\iota_n} P_{n-1} \rightarrow \Omega^{n-1} M \rightarrow 0,$$

gives an exact sequence,

$$0 \rightarrow \text{Hom}(\Omega^{n-1} M, N) \rightarrow \text{Hom}(P_{n-1}, N) \rightarrow \text{Hom}(\Omega^n M, N) \rightarrow 0,$$

so $\text{coker}(\iota_n^*) = 0$.

□

Proposition 2.5.8. *If $0 \rightarrow N \rightarrow I^0 \rightarrow I^1 \rightarrow \dots$ is an injective resolution of N then you can compute $\text{Ext}^n(M, N)$ as the cohomology of the cochain complex $\text{Hom}(M, \mathbf{I})$,*

$$0 \rightarrow \text{Hom}(M, I^0) \rightarrow \text{Hom}(M, I^1) \rightarrow \text{Hom}(M, I^2) \rightarrow \dots$$

Proof. Firstly, we break the injective resolution into short exact sequences,

$$\begin{array}{ccccccc} & & N & & & & \\ & & \parallel & & & & \\ 0 & \longrightarrow & \mathcal{U}^0 N & \longrightarrow & I^0 & \longrightarrow & \mathcal{U}^1 N \longrightarrow 0 \\ 0 & \longrightarrow & \mathcal{U}^1 N & \longrightarrow & I^1 & \longrightarrow & \mathcal{U}^2 N \longrightarrow 0 \end{array}$$

and so on. You then get a long exact sequence,

$$\begin{aligned} 0 &\rightarrow \text{Hom}(M, \mathcal{U}^i N) \rightarrow \text{Hom}(M, I^i) \rightarrow \text{Hom}(M, \mathcal{U}^{i+1} N) \rightarrow \\ &\rightarrow \text{Ext}^1(M, \mathcal{U}^i N) \rightarrow 0 \hookrightarrow \text{Ext}^1(M, \mathcal{U}^{i+1} N) \rightarrow \\ &\rightarrow \text{Ext}^2(M, \mathcal{U}^i N) \rightarrow 0 \hookrightarrow \dots \end{aligned}$$

Thus,

$$\begin{aligned} \text{Ext}^n(M, N) &\cong \text{Ext}^{n-1}(M, \mathcal{U}^i N) \cong \dots \cong \text{Ext}^1(M, \mathcal{U}^{n-1} N), \text{ by dimension shifting,} \\ &\cong \text{coker}(\text{Hom}(M, I^{n-1}) \rightarrow \text{Hom}(M, \mathcal{U}^n N)). \end{aligned}$$

Now, $0 \rightarrow \mathcal{U}^n N \rightarrow I^n \rightarrow I^{n+1}$ is exact, so,

$$0 \rightarrow \text{Hom}(M, \mathcal{U}^n N) \rightarrow \text{Hom}(M, I^n) \rightarrow \text{Hom}(M, I^{n+1}),$$

is exact. The claim follows. □

Proposition 2.5.9. *If Y is a module for any short exact sequence $0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ you have a long exact sequence,*

$$\begin{aligned} 0 &\rightarrow \text{Hom}(N, Y) \rightarrow \text{Hom}(M, Y) \rightarrow \text{Hom}(L, Y) \rightarrow \\ &\rightarrow \text{Ext}^1(N, Y) \rightarrow \text{Ext}^1(M, Y) \rightarrow \text{Ext}^1(L, Y) \rightarrow \\ &\rightarrow \text{Ext}^2(N, Y) \rightarrow \dots \end{aligned}$$

This is called the long exact sequence of $\text{Hom}(-, Y)$.

Proof. Let \mathbf{I} be an injective resolution of Y then the maps $f : L \rightarrow M$ and $g : M \rightarrow N$ induce maps of cochain complexes,

$$Hom(N, \mathbf{I}) \rightarrow Hom(M, \mathbf{I}) \rightarrow Hom(L, \mathbf{I}).$$

This is an exact sequence of cochain complexes since I^n is injective for all n . Now use the long exact sequence in cohomology from Remark 2.2.30. \square

Definition 2.5.10. For any short exact sequence $\mathbf{E} : 0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ we define an element $\hat{\mathbf{E}} \in Ext^1(N, L)$ as follows. The long exact sequence for $Hom(N, -)$ (see Proposition 2.5.6) gives a map $\delta : Hom(N, N) \rightarrow Ext^1(N, L)$, the connecting map, and $\hat{\mathbf{E}}$ is the image of id_N under this map.

Lemma 2.5.11. Fix a projective resolution of N , giving exact sequences,

$$0 \rightarrow \Omega^1 N \xrightarrow{\iota} P_0 \xrightarrow{\epsilon} N \rightarrow 0,$$

and,

$$Hom(P_0, L) \xrightarrow{\iota^*} Hom(\Omega^1 N, L) \rightarrow Ext^1(N, L) \rightarrow 0.$$

If $\mathbf{E} : 0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ is a short exact sequence then you can find maps α, β giving a commutative diagram,

$$\begin{array}{ccccccc} 0 & \longrightarrow & \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} & N \longrightarrow 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \parallel \\ 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & N \longrightarrow 0 \end{array}$$

Moreover, for any such commutative diagram the image of α in $Ext^1(N, L)$ is equal to $\hat{\mathbf{E}}$.

Proof. Existence of α, β : Since P_0 is projective and $g : M \rightarrow N$ is surjective (short exact sequence), by the definition of projective modules we can lift the map $P_0 \rightarrow N$ to a map β such that,

$$\begin{array}{ccc} & P_0 & \\ \exists \beta \swarrow & \downarrow \epsilon & \\ M & \xrightarrow{g} & N \end{array}$$

Then α exists by diagram chasing. As we have a projective resolution of N , we can apply $Hom(N, -)$ to \mathbf{E} to obtain (Propn. 2.5.6),

$$0 \rightarrow Hom(N, L) \rightarrow Hom(N, M) \rightarrow Hom(N, N) \xrightarrow{\delta} Ext^1(N, L) \rightarrow \dots$$

and so find the connecting map $\delta : Hom(N, N) \rightarrow Ext^1(N, L)$. Note that this is the connecting map in cohomology for the exact sequence of cochain complexes,

$$0 \rightarrow Hom(\mathbf{P}, L) \rightarrow Hom(\mathbf{P}, M) \rightarrow Hom(\mathbf{P}, N) \rightarrow 0.$$

This begins,

$$\begin{array}{ccccccc}
& & 0 & & 0 & & 0 \\
& & \downarrow & & \downarrow & & \downarrow \\
0 & \longrightarrow & \text{Hom}(P_0, L) & \longrightarrow & \text{Hom}(P_0, M) & \longrightarrow & \text{Hom}(P_0, N) \longrightarrow 0 \\
& & \downarrow & & \downarrow & & \downarrow \\
0 & \longrightarrow & \text{Hom}(P_1, L) & \longrightarrow & \text{Hom}(P_1, M) & \longrightarrow & \text{Hom}(P_1, N) \longrightarrow 0 \\
& & \downarrow & & \downarrow & & \downarrow
\end{array}$$

Then $\text{Hom}(N, N) \cong \text{Ext}^0(N, N) = H^0(\mathbf{P}, N)$ and,

$$\begin{aligned}
H^0(\mathbf{P}, N) &= \text{cohomology at } \text{Hom}(P_0, N), \\
&= \frac{\ker(\text{Hom}(P_0, N) \rightarrow \text{Hom}(P_1, N))}{\text{im}(0 \rightarrow \text{Hom}(P_0, N))}, \\
&= \ker(\text{Hom}(P_0, N) \rightarrow \text{Hom}(P_1, N)),
\end{aligned}$$

and so we have id_N corresponding to $\bar{\epsilon}$. From earlier β is a lifting of ϵ in $\text{Hom}(P_1, M)$. Let γ be the corresponding element in $\text{Hom}(P_1, L)$. Then the diagram,

$$\begin{array}{ccccccc}
& & P_1 & \xrightarrow{d_1} & P_0 & \xrightarrow{\epsilon} & N \longrightarrow 0 \\
& & \downarrow \gamma & & \downarrow \beta & & \parallel \\
0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} & N \longrightarrow 0
\end{array}$$

commutes. However, the composition,

$$\begin{array}{ccc}
P_2 & \xrightarrow{d_2} & P_1 \\
& & \downarrow \gamma \\
& & L \xrightarrow{f} M
\end{array}$$

is equal to,

$$\begin{array}{ccccc}
P_2 & \xrightarrow{d_2} & P_1 & \xrightarrow{d_1} & P_0 \\
& & & & \downarrow \beta \\
& & & & M
\end{array}$$

and so is zero as $d_1 d_2 = 0$. Hence, since $f : L \rightarrow M$ is injective, the composition $\gamma d_2 : P_2 \rightarrow L$ is zero. Thus γ induces a map $P_1/\text{Im}(d_2) \rightarrow L$, i.e. $\alpha : \Omega^1 N \rightarrow L$. \square

Theorem 2.5.12. *There exists a bijection Θ ,*

$$\left\{ \begin{array}{l} \text{equivalence classes of} \\ \text{short exact sequences} \\ 0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0 \end{array} \right\} \longrightarrow \text{Ext}^1(N, L)$$

Proof. Firstly we want to show that Θ is well defined:

Consider two equivalent exact sequences \mathbf{E}, \mathbf{E}' , they become the bottom two rows of the diagram,

$$\begin{array}{ccccccc} \mathbf{F} : & 0 & \longrightarrow & \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} N \longrightarrow 0 \\ & & & \downarrow \alpha & & \downarrow \beta & \parallel \\ \mathbf{E} : & 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} N \longrightarrow 0 \\ & & & \parallel & & \downarrow \cong & \parallel \\ \mathbf{E}' : & 0 & \longrightarrow & L & \xrightarrow{f'} & M' & \xrightarrow{g'} N \longrightarrow 0 \end{array}$$

where θ is an isomorphism. So \mathbf{E} and \mathbf{E}' give rise to the same map $\gamma : P_1 \rightarrow L$ (or $\alpha : \Omega^1 \rightarrow L$) by Lemma 2.5.11 and so $\hat{E} = \hat{E}'$.

Secondly, we need to show that Θ is surjective:

Set $g \in \text{Ext}^1(N, L)$. Then this corresponds to some $\alpha \in \text{Hom}(\Omega^1 N, L)$ as in the long exact sequence,

$$0 \rightarrow \text{Hom}(N, L) \rightarrow \text{Hom}(P_0, L) \rightarrow \text{Hom}(\Omega^1 N, L) \xrightarrow{\delta} \text{Ext}^1(N, L) \rightarrow 0 \rightarrow \dots$$

δ is surjective. So we have,

$$\begin{array}{ccccccc} \mathbf{F} : & 0 & \longrightarrow & \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} N \longrightarrow 0 \\ & & & \downarrow \alpha & & \downarrow & \parallel \\ \mathbf{E} : & 0 & \longrightarrow & L & \longrightarrow & M & \longrightarrow N \longrightarrow 0 \end{array}$$

where \mathbf{E} is the pushout of \mathbf{F} along α . By construction, \mathbf{E} is an exact sequence, unique up to equivalence, so any element of $\text{Ext}^1(N, L)$ is the image of an equivalence class of short exact sequences.

Finally, we prove that Θ is injective: If two short exact sequences \mathbf{E}, \mathbf{E}' give the same element $\hat{E} \in \text{Ext}^1(N, L)$ then we have diagrams,

$$\begin{array}{ccccccc} \mathbf{F} : 0 \rightarrow \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} & N & \rightarrow 0 & \mathbf{F}' : 0 \rightarrow \Omega^1 N \xrightarrow{\iota} P_0 \xrightarrow{\epsilon} N \rightarrow 0 \\ \downarrow \alpha & & \downarrow \beta & & \parallel & & \downarrow \alpha' & & \downarrow \beta' & & \parallel \\ \mathbf{E} : 0 \rightarrow L & \xrightarrow{f} & M & \xrightarrow{g} & N & \rightarrow 0 & \mathbf{E}' : 0 \rightarrow L \xrightarrow{f'} M' \xrightarrow{g'} N \rightarrow 0 \end{array} \quad \&$$

with $\alpha' - \alpha \in \text{im}(\text{Hom}(P_0, L) \xrightarrow{\iota^*} \text{Hom}(\Omega^1 N, L))$ from the long exact sequence,

$$0 \rightarrow \text{Hom}(N, L) \rightarrow \text{Hom}(P_0, L) \xrightarrow{\iota^*} \text{Hom}(\Omega^1 N, L) \xrightarrow{\delta} \text{Ext}^1(N, L) \rightarrow 0 \rightarrow \dots$$

and so $\text{im}(\iota^*) = \ker(\delta)$ by exactness and so we can map $\alpha' - \alpha \mapsto \hat{E} - \hat{E} = 0$. Now say $\alpha' - \alpha = \phi \circ \iota$ with $\phi : P_0 \rightarrow L$, then,

$$\begin{array}{ccccccc} \mathbf{F} : & 0 & \longrightarrow & \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} N \longrightarrow 0 \\ & & & \downarrow \alpha' & & \downarrow \beta + f\phi & \parallel \\ \mathbf{E} : & 0 & \longrightarrow & L & \xrightarrow{f} & M & \xrightarrow{g} N \longrightarrow 0 \end{array}$$

Hence by the uniqueness of pushouts, \mathbf{E} and \mathbf{E}' are equivalent. \square

Proposition 2.5.13. *The split exact sequences of an equivalence class of extensions of N by L correspond to the zero element of $\text{Ext}^1(N, L)$.*

Proof. Lemma 2.2.20 gives that any two split extensions of N by L are equivalent, and so in the same equivalence class. Note that if $\mathbf{E} : 0 \rightarrow L \rightarrow M \rightarrow N \rightarrow 0$ splits then as $M \cong L \oplus N$ (Cor. 2.2.18), \mathbf{E} is equivalent to $0 \rightarrow L \rightarrow L \oplus N \rightarrow N \rightarrow 0$. Relabel this exact sequence \mathbf{E} . Let $0 \rightarrow P_1 \rightarrow P_0 \rightarrow N \rightarrow 0$ be the projective resolution of N . Then, by Lemma 2.5.11 we have a commutative diagram,

$$\begin{array}{ccccccc} 0 & \longrightarrow & \Omega^1 N & \xrightarrow{\iota} & P_0 & \xrightarrow{\epsilon} & N \longrightarrow 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \parallel \\ 0 & \longrightarrow & L & \longrightarrow & L \oplus N & \longrightarrow & N \longrightarrow 0 \end{array}$$

and applying $\text{Hom}(-, L)$ to the top row gives the long exact sequence,

$$0 \rightarrow \text{Hom}(N, L) \rightarrow \text{Hom}(P_0, L) \rightarrow \text{Hom}(\Omega^1 N, L) \xrightarrow{\delta} \text{Ext}^1(N, L) \rightarrow 0 \rightarrow \dots$$

with $\delta(\alpha) = \hat{E}$. However, $\alpha = 0$ by diagram chasing, and so $\hat{E} = 0$. \square

This result is interesting as it means, as Rotman points out in [3], the non-zero elements of $\text{Ext}^1(N, L)$ describe nonsplit extensions of N by L .

Definition 2.5.14. The *projective dimension* of a module M is the smallest $n \in \mathbb{Z}$ such that there is a finite projective resolution of M ,

$$0 \rightarrow P_n \rightarrow \dots \rightarrow P_1 \rightarrow P_0 \rightarrow M \rightarrow 0.$$

It is denoted $\text{pd}(M) = n$. If no such finite projective resolution exists, then $\text{pd}(M) = \infty$.

Definition 2.5.15. The *global dimension* of the ring R is the maximum of the projective dimensions of its modules.

Proposition 2.5.16. *Let M be a module and $n \geq 0$. The following are equivalent:*

- (i) $pd(M) = n$.
- (ii) $Ext^{n+1}(M, N) = 0$ for all modules N .

Proof. (i) \Rightarrow (ii): This is trivial, as if $P_{n+1} = 0$ then the cohomology of the long exact sequence will also be equal to zero.

(ii) \Rightarrow (i): If \mathbf{P} is a projective resolution then there is an exact sequence,

$$0 \rightarrow \Omega^n M \xrightarrow{\iota} P_{n-1} \rightarrow \dots \rightarrow P_0 \rightarrow M \rightarrow 0,$$

and so it suffices to prove $\Omega^n M$ is projective as then this exact sequence is the required projective resolution. This condition is satisfied if $Ext(\Omega^n M, N) = 0$ for all N . The exact sequence,

$$0 \rightarrow \Omega^n M \rightarrow P_{n-1} \rightarrow \Omega^{n-1} M \rightarrow 0,$$

gives a long exact sequence which includes,

$$\dots \rightarrow Ext^1(P_{n-1}, N) \rightarrow Ext^1(\Omega^n M, N) \rightarrow Ext^2(\Omega^{n-1} M, N) \rightarrow Ext^2(P_{n-1}, N) \rightarrow \dots$$

However, P_{n-1} is projective so $Ext^i(P_{n-1}, N) = 0$ for all i and so we have,

$$\dots \rightarrow 0 \rightarrow Ext^1(\Omega^n M, N) \rightarrow Ext^2(\Omega^{n-1} M, N) \rightarrow 0 \rightarrow \dots$$

Hence, $Ext^1(\Omega^n M, N) \cong Ext^2(\Omega^{n-1} M, N)$. Then by dimension shifting we get,

$$Ext^2(\Omega^{n-1} M, N) \cong Ext^3(\Omega^{n-2} M, N) \cong \dots \cong Ext^{n+1}(\Omega^0 M, N) = Ext^{n+1}(M, N),$$

$= 0.$

□

Chapter 3

Representation of Quivers

3.1 Quivers and Path Algebras

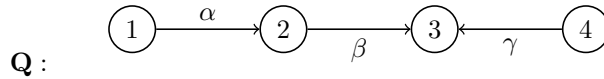
Definition 3.1.1. A *quiver* is defined as the tuple of sets and functions, $\mathbf{Q} = (Q_0, Q_1, s, t : Q_1 \rightarrow Q_0)$ such that:

- Q_0 is the set of vertices, which we will set to be the finite set $\{1, 2, \dots, n\}$.
- Q_1 is the set of arrows, which we will also set to be finite.
- Functions s, t such that an arrow $\rho \in Q_1$ *starts* at the vertex $s(\rho) \in Q_0$ and *terminates* at the vertex $t(\rho) \in Q_0$, i.e. $\rho : s(\rho) \rightarrow t(\rho)$.

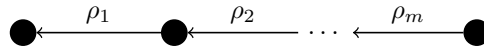
Example 3.1.2. A quiver $Q = (Q_0, Q_1, s, t : Q_1 \rightarrow Q_0)$ where $Q_0 = \{1, 2, 3, 4\}$, $Q_1 = \{\alpha, \beta\}$, and s, t are defined such that;

$$\begin{aligned} s : Q_1 &\rightarrow Q_0, & \alpha &\mapsto 1, \beta \mapsto 2, \gamma \mapsto 4 \\ t : Q_1 &\rightarrow Q_0, & \alpha &\mapsto 2, \beta \mapsto 3, \gamma \mapsto 3, \end{aligned}$$

looks like,



Definition 3.1.3. A *non-trivial path*, p , in the quiver Q , is a sequence of arrows ρ_1, \dots, ρ_n which satisfies $t(\rho_{i+1}) = s(\rho_i)$ for all $1 \leq i < n$. Pictorially,



The starting and terminating vertex of a path p , $s(\rho_1)$ and $t(\rho_1)$, are denoted $s(p)$ and $t(p)$, respectively.

Notation 3.1.4. In this report the arrows in a path will be ordered the same way as the composition of functions, as in [2], however, be aware that other publications may order the arrows the opposite way.

Definition 3.1.5. The *trivial path* is the path which contains no arrows, i.e. it is a single vertex, and is denoted e_i where the vertex is i .

Example 3.1.6. The paths of the quiver in Example 3.1.2 are:

$$p_1 = e_1, \quad p_2 = e_2, \quad p_3 = e_3, \quad p_4 = e_4, \quad p_5 = \alpha, \quad p_6 = \beta, \quad p_7 = \gamma, \quad p_8 = \beta\alpha.$$

However, $\gamma\beta\alpha$ is not a path because $t(\beta) = 3 \neq s(\gamma) = 2$.

Definition 3.1.7. A *path algebra* kQ is the k -algebra which has a basis all the paths in Q , and the product of two paths p, q is defined as,

$$pq = \begin{cases} \text{obvious composition} & \text{if } t(q) = s(p), \\ 0 & \text{otherwise.} \end{cases}$$

This multiplication is associative.

Example 3.1.8. If we once again use the quiver Q from Example 3.1.2, then, from Example 3.1.6, we know the basis of the path algebra kQ will be,

$$\{e_1, e_2, e_3, e_4, \alpha, \beta, \gamma, \beta\alpha\}.$$

The product of β and α is $\beta\alpha$, but the product of α and β is zero, and the product of e_2 and α is just α .

Example 3.1.9. If Q is the following quiver,

$$\mathbf{Q} : \quad \alpha \curvearrowright (1) \curvearrowleft \beta$$

forms the path algebra $kQ \cong k \langle X, Y \rangle$, the free, associative algebra on two letters. In fact, if we have a quiver with a single vertex and n loops, then this can be associated with the free, associative algebra on n letters.

Remark 3.1.10. Recall that $UT_n(k)$ is the algebra of $n \times n$ upper triangular matrices over a field k . Similarly, $LT_n(k)$ is the algebra of $n \times n$ lower triangular matrices over a field k .

Example 3.1.11. If we have the quiver,

$$\mathbf{Q} : \quad (1) \xrightarrow{\alpha} (2) \xrightarrow{\beta} (3) \xrightarrow{\gamma} (4)$$

the the path algebra, $kQ \cong UT_4(k)$ by the isomorphism,

$$\begin{aligned} &\lambda_1 e_1 + \lambda_2 e_2 + \lambda_3 e_3 + \lambda_4 e_4 + \lambda_5 \alpha + \\ &\lambda_6 \beta + \lambda_7 \gamma + \lambda_8 \beta\alpha + \lambda_9 \gamma\beta\alpha + \lambda_{10} \gamma\beta \mapsto \begin{pmatrix} \lambda_4 & \lambda_7 & \lambda_{10} & \lambda_9 \\ 0 & \lambda_3 & \lambda_6 & \lambda_8 \\ 0 & 0 & \lambda_2 & \lambda_5 \\ 0 & 0 & 0 & \lambda_1 \end{pmatrix} \end{aligned}$$

Generally, a quiver of the form,

$$\mathbf{Q}' : \quad (1) \xrightarrow{\alpha} (2) \xrightarrow{\beta} \dots \xrightarrow{\gamma} (n)$$

induces a path algebra $kQ' \cong UT_n(k)$ for any n .

Example 3.1.12. In fact, we find that if Q is the same quiver as above in Example 3.1.11, then $kQ \cong LT_4(k)$ as well, through the isomorphism,

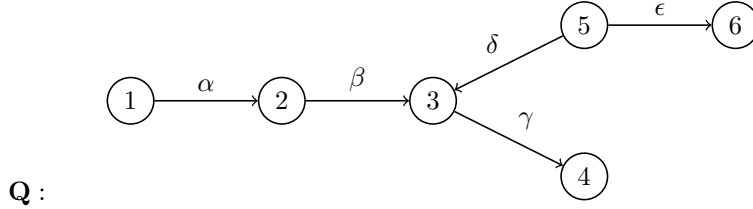
$$\lambda_1 e_1 + \lambda_2 e_2 + \lambda_3 e_3 + \lambda_4 e_4 + \lambda_5 \alpha + \lambda_6 \beta + \lambda_7 \gamma + \lambda_8 \beta \alpha + \lambda_9 \gamma \beta \alpha + \lambda_{10} \gamma \beta \mapsto \begin{pmatrix} \lambda_1 & 0 & 0 & 0 \\ \lambda_5 & \lambda_2 & 0 & 0 \\ \lambda_8 & \lambda_6 & \lambda_3 & 0 \\ \lambda_9 & \lambda_{10} & \lambda_7 & \lambda_4 \end{pmatrix}.$$

Once again, this extends to the general case that, $kQ' \cong LT_n(k)$.

Example 3.1.13. In a more general case, as long as there is only one path between any two vertices, we can identify kQ with the following subalgebra of $M_n(k)$,

$$\{M \in M_n(k) : M_{ij} = 0 \text{ if there is no path from } j \text{ to } i\}.$$

For instance, if we have the quiver,



the we can see that the path algebra kQ is isomorphic to the subalgebra with matrices of the form,

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{pmatrix}$$

Remark 3.1.14. Note that the idea here has some parallels to similar results for directed graphs in graph theory.

The following results about the idempotents of path algebras are from [2], however, we have either given a proof or expanded upon the one given. For the following results we set $A = kQ$ and the e_i are the trivial paths of Q .

Definition 3.1.15. Let Λ be an algebra.

- An element $e \in \Lambda$ is said to be *idempotent* if $ee = e$.
- Idempotent elements $e, e' \in \Lambda$ are said to be *orthogonal* if $ee' = e'e = 0$.
- A nonzero idempotent element $e \in \Lambda$ is said to be *primitive* if whenever $e = e' + e''$, with $e', e'' \in \Lambda$ orthogonal idempotents then either $e' = 0$ or $e'' = 0$.

Lemma 3.1.16. The e_i are orthogonal idempotents in A . Thus $\sum_{i=1}^n e_i = 1_A$.

Proof. Obviously, $e_i e_j = 0$ when $i \neq j$ because $t(e_j) \neq s(e_i)$ because they are the trivial paths at different vertices, i and j . Similarly, if we have the product $e_i e_i$ then the composition makes sense here because $t(e_i) = s(e_i)$, but the composition is just e_i because if we travel along the trivial path e_i twice, then this is just the same as travelling the trivial path.

If we have some path p of the quiver, then bear in mind that,

$$e_i p = \begin{cases} e_i p = p & \text{if } i = t(p), \\ 0 & \text{otherwise.} \end{cases}$$

Hence, the sum of the trivial paths acting on our path p becomes,

$$\left(\sum_{i=1}^n e_i \right) p = (e_1 + e_2 + \cdots + e_n) p = e_i p = p = 1_A p,$$

because only one of the e_i in the sum will satisfy $i = t(p)$ and all the rest will give zero. Similarly, we can show that $p \left(\sum_{i=1}^n e_i \right) = p 1_A$. \square

Lemma 3.1.17. *The spaces Ae_i and $e_j A$ have as bases all the paths starting at i and all the paths terminating at j , respectively. Moreover, the space $e_j Ae_i$ has as a basis the paths that start at i and terminate at j .*

Proof. Set $i \in Q_0$. Let P be the set of all paths in Q which start at the vertex i . Note that as Q may have oriented cycles, P is not necessarily finite dimensional. We have $P \subset Ae_i$ since if $q \in P$ then $p = pe_i \in Ae_i$. Next want to show that P is linearly independent and spans Ae_i . Firstly, recall from the definition of a path algebra that the set of all paths in Q forms a basis for A . Hence, all the paths in Q are linearly independent and moreover so are all the paths in P . Now suppose we have an element $ae_i \in Ae_i$ then $a \in A$ and so $a = \sum_j \lambda_j p_j$, however, we can rewrite this $a = \sum_r \mu_r q_r + \sum_s \mu'_s q'_s$ where $q_r \in P$ and the q'_s are paths in Q not starting at vertex i . Then, $ae_i = \sum_r \mu_r q_r$ and so P spans Ae_i . Thus, we can see that the basis of Ae_i must be all the paths starting at i . Similarly, as $e_j A$ is a subspace of A and so following a similar argument we can see that its basis must be all the paths terminating at j . The result for $e_j Ae_i$ follows from these as it simply the intersection of the two spaces. \square

Lemma 3.1.18. *$A = \bigoplus_{i=1}^n Ae_i$, so each Ae_i is a projective left A -module.*

Proof. Firstly, let us convince ourselves that A is indeed equal to $\bigoplus_{i=1}^n Ae_i$. Recall from Lemma 3.1.16 that $1_A = \sum_{i=1}^n e_i$ and it is also clear that $Ae_i \cap Ae_j = \{0\}$ for all $i \neq j$. Hence, $A = Ae_1 \oplus \cdots \oplus Ae_n$.

From Lemma 3.1.17 we know that for each i , the basis of Ae_i are all the paths starting at i and so $\bigoplus_{i=1}^n Ae_i$ must have as a basis all the paths starting at every vertex in Q , hence all the paths in Q . Thus $A = \bigoplus_{i=1}^n Ae_i$. Also, each Ae_i is obviously a left A -module with the action defined as multiplication by e_i . Hence, each Ae_i is a projective, left A -module. \square

Remark 3.1.19. Similarly, $A = \bigoplus_{i=1}^n e_j A$, so each $e_j A$ is a projective, right A -module.

Lemma 3.1.20. *If X is a left A -module, then $\text{Hom}_A(Ae_i, X) \cong e_i X$.*

Proof. Want to show that there are some maps f and g ,

$$f : \text{Hom}_A(Ae_i, X) \rightarrow e_i X \quad \& \quad g : e_i X \rightarrow \text{Hom}_A(Ae_i, X)$$

such that $gf = \text{id}_{\text{Hom}_A(Ae_i, X)}$ and $fg = \text{id}_{e_i X}$. We can define a map $f : \text{Hom}_A(Ae_i, X) \rightarrow e_i X$ as follows: Given a map $\theta \in \text{Hom}_A(Ae_i, X)$ set $f(\theta) = \theta(e_i)$. Then $\theta(e_i) \in Xe_i$ since $\theta(e_i) = \theta(e_i^2) = e_i\theta(e_i) \in e_i X$. Hence, f maps a homomorphism from $\text{Hom}_A(Ae_i, X)$ to an element in $e_i X$. We can define a map $g : e_i X \rightarrow \text{Hom}_A(Ae_i, X)$ as follows: Consider the map $g(x) : Ae_i \rightarrow X$, $a \mapsto ax$ for some $a \in A, x \in X$. This is an A -module homomorphism as,

$$\begin{aligned} g(x)(a+b) &= (a+b)x = ax + bx = g(x)(a) + g(x)(b) & a, b \in Ae_i, \\ g(x)(\lambda a) &= \lambda ax = \lambda g(x)(a) & \lambda \in A, a \in Ae_i. \end{aligned}$$

Hence, $g(x) \in \text{Hom}_A(Ae_i, X)$. Now, set $g : e_i X \rightarrow \text{Hom}_A(Ae_i, X)$, $x \mapsto g(x)$. Now to show that f and g are inverse constructions of one another. Let $x \in e_i X$, then,

$$\begin{aligned} fg(x) &= f(g(x)), \\ &= g(x)(e_i), \\ &= e_i x, \\ &= x. \end{aligned}$$

Hence, $fg = \text{id}_{e_i X}$. Also, for some $\theta \in \text{Hom}_A(Ae_i, X)$, $a \mapsto \theta(a)$ for $a \in Ae_i$, we have, $gf(\theta) = g(\theta(e_i))$, but the action of g is,

$$\begin{aligned} g(\theta(e_i))(a) &= a\theta(e_i), \\ &= \theta(ae_i), \text{ as } \theta \text{ is a homomorphism and } a \in Ae_i \subset A, \\ &= \theta(a), \text{ as } a \in Ae_i, \end{aligned}$$

but this is just the action of θ . Hence, $gf = \text{id}_{\text{Hom}_A(Ae_i, X)}$. Thus f and g are inverse constructions of one another. \square

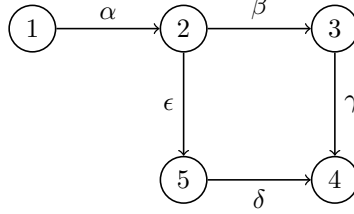
Lemma 3.1.21. *If $a \in Ae_i, b \in e_i A$ and a, b both nonzero then $ab \neq 0$.*

Proof. If $a \in Ae_i$ it is a linear combination of paths in Q which start at vertex i and so we can write $a = \sum_{i=0}^r p_i$ where the p_i are the linear combinations of all the terms in a which have paths of length i and r is the maximal length of a path appearing in the linear combination of a . Similarly, we can write $b = \sum_{j=0}^s q_j$. Then,

$$\begin{aligned} ab &= (p_0 + p_1 + \dots + p_r)(q_0 + q_1 + \dots + q_s), \\ &= p_0 q_0 + \dots + p_r q_s. \end{aligned}$$

Suppose to the contrary that this sum is equal to zero, this then implies that $p_r q_s$ cancels with other terms in the sum, but this is not possible as the paths in $p_r q_s$ have the maximal length in the sum. Hence it must be zero, a contradiction. Thus $ab \neq 0$. \square

Example 3.1.22. Let $A = kQ$ where $k = Q$ and the quiver Q is,



If we have $a = 3\gamma\beta + \delta\epsilon - \beta \in Ae_2$ and $b = 2\alpha \in e_2A$. Write $a = p_0 + p_1 + p_2$ where $p_0 = 0$, $p_1 = -\beta$ and $p_2 = 3\gamma\beta + \delta\epsilon$. Similarly, write $b = q_1$ where $q_0 = 0$, $q_1 = \alpha$. Then,

$$\begin{aligned}
ab &= (p_1 + p_2)(q_1), \\
&= p_1q_1 + p_2q_1, \\
&= -\beta\alpha + (3\gamma\beta + \delta\epsilon)\alpha, \\
&= -\beta\alpha + 3\gamma\beta\alpha + \delta\epsilon.
\end{aligned}$$

We present the following property of primitive idempotents from [14] without proof.

Proposition 3.1.23. *An idempotent $e \in A$ is primitive if and only if the algebra $eAe \cong \text{End}(eA)$ has only two idempotents 0 and e .*

Lemma 3.1.24. *The e_i are primitive idempotents.*

Proof. From Lemma 3.1.20 we know that $\text{End}_A(Ae_i) \cong e_iAe_i$ and if this contains an idempotent ϵ , then $\epsilon^2 = \epsilon = \epsilon e_i$, so $\epsilon(e_i - \epsilon) = 0$, but from Lemma 3.1.21 we know that this can not happen if $\epsilon, (e_i - \epsilon) \neq 0$, thus we must have that either $\epsilon = 0$ or $\epsilon = e_i$ and the result follows. \square

The following is from a claim in [11].

Lemma 3.1.25. *Ae_i is an indecomposable module.*

Proof. Suppose to the contrary that Ae_i is decomposable, then we can write $Ae_i = N_1 \oplus N_2$ with N_1, N_2 nonzero. As $e_i \in Ae_i$ there exist unique $n_1 \in N_1$ and $n_2 \in N_2$ such that $e_i = n_1 + n_2$. Now,

$$e_i = e_i^2 = (n_1 + n_2)^2 = n_1^2 + n_1n_2 + n_2n_1 + n_2^2. \quad (3.1)$$

However, $n_1 = n_1e_i$ and $n_2 = n_2e_i$ as $n_1, n_2 \in Ae_i$ and so we also have,

$$e_i = e_i^2 = (n_1 + n_2)e_i = e_in_1 + e_in_2,$$

and so $e_in_1 + e_in_2 = n_1 + n_2$ (*). Since N_1, N_2 are submodules we must have $e_in_1 \in N_1$ and $e_in_2 \in N_2$, and so (*) and the fact $N_1 \oplus N_2$ is a direct sum, we have $e_in_1 = n_1$. This implies $n_2n_1 + n_1^2 = n_1$ while $n_1 = n_1e_1$ implies $n_1 = n_1^2 + n_1n_2$. Thus $n_2n_1 = n_1n_2 \in N_1 \cap N_2$ and so are both equal to zero. Therefore, 3.1 now gives us $n_1 + n_2 = e_i = n_1^2 + n_2^2$. Thus both n_1 and n_2 are orthogonal idempotents, contradicting that e_i is primitive. \square

Definition 3.1.26. Define Ae_iA to be the path algebra induced by all paths in Q which pass through j .

Lemma 3.1.27. If $e_i \in Ae_jA$ then $i = j$.

Proof. It is clear that a basis of Ae_jA is all the paths in A which pass through the vertex j . By the definition of the trivial path, e_i cannot pass through the vertex j unless $i = j$ and so if $e_i \in Ae_jA$ we must have that $i = j$. \square

Definition 3.1.28. Two idempotent elements e_i, e_j are said to be *equivalent* if and only if there exists some $u \in e_iAe_j$ and $v \in e_jAe_i$ such that $uv = e_i$ and $vu = e_j$.

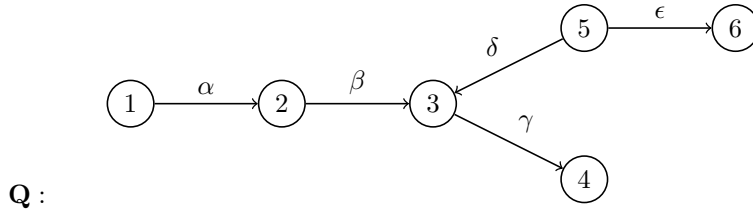
Lemma 3.1.29. The e_i are inequivalent.

Proof. From Lemma 3.1.20 we can see that $\text{Hom}(Ae_i, Ae_j) \cong e_iAe_j$ and $\text{Hom}(Ae_j, Ae_i) \cong e_jAe_i$, and so there exist some inverse isomorphisms $f : Ae_i \rightarrow Ae_j$ and $g : Ae_j \rightarrow Ae_i$ corresponding to elements u and v respectively. Then we have $uv = e_i$ and $vu = e_j$. However, this means that the path e_i must pass through the vertex j at some point, a contradiction. \square

Corollary 3.1.30. $Ae_i \not\cong Ae_j$ for $i \neq j$.

Proof. This follows from 3.1.29, as it implies that the maps f, g could not have been inverse isomorphisms. \square

Example 3.1.31. Consider the quiver from Example 3.1.13,



then we have the following examples displaying the previous results for the idempotents of kQ . Let $A = kQ$.

1. We can see that $e_1e_1 = e_1$ and $e_1e_2 = 0$. Also, $1_A = e_1 + e_2 + e_3 + e_4 + e_5 + e_6$ and so

$$\begin{aligned}
 1_A \gamma \beta &= (e_1 + e_2 + e_3 + e_4 + e_5 + e_6) \gamma \beta, \\
 &= e_1 \gamma \beta + e_2 \gamma \beta + e_3 \gamma \beta + e_4 \gamma \beta + e_5 \gamma \beta + e_6 \gamma \beta, \\
 &= e_4 \gamma \beta, \\
 &= \gamma \beta.
 \end{aligned}$$

2. Now we can see that Ae_1 is spanned by all the paths starting at vertex 1,

as,

$$\begin{aligned}
Ae_1 &= \{ae_1 : a \in A\}, \\
&= \text{span}_k \left\{ \sum p e_1 : p \text{ is in the basis of } A \right\}, \\
&= \text{span}_k \{e_1 e_1 + e_2 e_1 + e_3 e_1 + e_4 e_1 + e_5 e_1 + e_6 e_1 + \alpha e_1 + \\
&\quad \beta e_1 + \gamma e_1 + \delta e_1 + \epsilon e_1 + \beta \alpha e_1 + \gamma \beta e_1 + \gamma \delta e_1 + \gamma \beta \alpha e_1\}, \\
&= \text{span}_k \{e_1 + \alpha + \beta \alpha + \gamma \beta \alpha\}, \\
&= \text{span}_k \{\text{all paths starting at vertex 1}\}.
\end{aligned}$$

Similarly, we can see that,

$$\begin{aligned}
e_3 A &= \{e_3 a : a \in A\}, \\
&= \text{span}_k \{e_3 + \beta + \delta + \beta \alpha\}, \\
&= \text{span}_k \{\text{all the paths terminating at vertex 3}\}.
\end{aligned}$$

Then we can see that,

$$\begin{aligned}
e_3 A e_1 &= \{e_3 a e_1 : a \in A\}, \\
&= \text{span}_k \{\beta \alpha\}, \\
&= \text{span}_k \{\text{all paths starting at vertex 1 and terminating at vertex 3}\}.
\end{aligned}$$

3. We can see that,

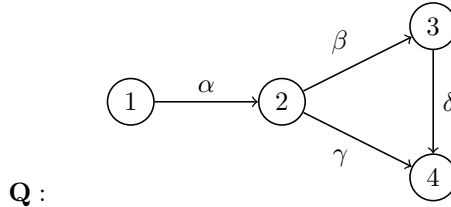
$$\begin{aligned}
\bigoplus_{i=1}^6 A e_i &= A e_1 \oplus A e_2 \oplus A e_3 \oplus A e_4 \oplus A e_5 \oplus A e_6, \\
&= \text{span}_k \{e_1 + \alpha + \beta \alpha + \gamma \beta \alpha\} \oplus \text{span}_k \{e_2 + \beta + \gamma \beta\} \oplus \text{span}_k \{e_3 + \gamma\} \\
&\quad \oplus \text{span}_k \{e_4\} \oplus \text{span}_k \{e_5 + \delta + \epsilon + \gamma \delta\} \oplus \text{span}_k \{e_6\}, \\
&= A.
\end{aligned}$$

Lemma 3.1.32. *A is finite dimensional if and only if Q has no oriented cycles.*

Proof. \Rightarrow : If Q has an oriented cycle c then it will have basis elements c, c^2, c^3, \dots and so A will have an infinite basis.

\Leftarrow : If Q has no oriented cycles then it must have a finite number of paths and so the basis of A will be finite and hence A will be finite dimensional. \square

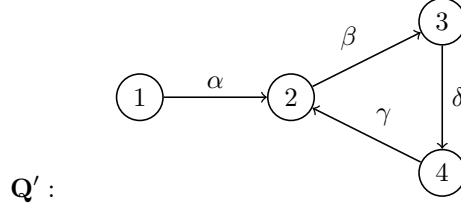
Example 3.1.33. If we consider the quiver Q,



and we can see that Q has the paths $e_1, e_2, e_3, e_4, \alpha, \beta, \gamma, \delta, \beta \alpha, \gamma \alpha, \beta \delta, \delta \beta \alpha$, and so the basis of A is $\{e_1, e_2, e_3, e_4, \alpha, \beta, \gamma, \delta, \beta \alpha, \gamma \alpha, \beta \delta, \delta \beta \alpha\}$, which is finite, and

so A is finite dimensional.

However, if we have the quiver Q' ,



it has paths $e_1, e_2, e_3, e_4, \alpha, \beta, \gamma, \delta, \beta\alpha, \delta\beta, \gamma\delta, \delta\beta\alpha, \gamma\delta\beta\alpha, \beta\gamma\delta\beta\alpha, \delta\beta\gamma\delta\beta\alpha, \dots$, and so on, an infinite number of paths, meaning that the basis of A is infinite and hence A is not finite dimensional.

Definition 3.1.34. For a module M the *Jacobson Radical* is defined,

$$J(M) = \text{rad}(M) = \bigcap \text{maximal submodules of } M.$$

Definition 3.1.35. The *centre* of an algebra A is defined to be,

$$Z(A) = \{x \in A : ax = xa \text{ for all } a \in A\}.$$

The following will be provided as properties of path algebras as in [2] and will not be proven.

Remark 3.1.36. • A is prime, i.e. $IJ \neq 0$ for two sided ideals $I, J \neq 0$ if and only if for all $i, j \in Q_0$ there exists a path i to j .

- A is left noetherian if and only if, if there is an oriented cycle through the vertex i , then only one arrow starts at the vertex i .
- The basis of $J(A)$ is $\{\text{path } i \text{ to } j : \text{there is no path from } j \text{ to } i\}$.
- The centre of A is $k \times k \times \dots k[T] \times k[T] \times \dots$, with one factor for each connected component C of Q , and that the factor is $k[T]$ if and only if C is an oriented cycle.

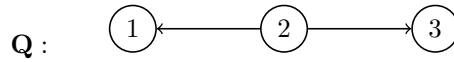
3.2 Representations of Quivers

In this section we consider quivers without oriented cycles.

Definition 3.2.1. A *representation* of a quiver Q is $X = (\{X_i\}, \{X_\rho\})$ where,

- there is a vector spaces X_i corresponding to each $i \in Q_0$, and,
- a linear map $X_\rho : X_{s(\rho)} \rightarrow X_{t(\rho)}$ for each $\rho \in Q_1$.

Example 3.2.2. Let Q be the quiver,



then we can have representations X and Y ,

$$X : \quad k \xleftarrow{1} k \xrightarrow{1} k \quad \& \quad Y : \quad k \xleftarrow{1} k \longrightarrow 0$$

Definition 3.2.3. Let $X = (\{X_i\}, \{X_\rho\})$ and $X' = (\{X'_i\}, \{X'_\rho\})$ be representations of Q .

- A *morphism* $\theta : X \rightarrow X'$ between representations is given by linear maps $\theta_i : X_i \rightarrow X'_i$ for each $i \in Q_0$ satisfy $X'_\rho \theta_{s(\rho)} = \theta_{t(\rho)} X_\rho$ for each $\rho \in Q_1$.
- The *composition* of morphisms, $\theta : X \rightarrow X'$ with $\phi : X' \rightarrow X''$ is given by $(\phi\theta)_i = \phi_i \theta_i$.

The following example is given as an exercise in [2].

Example 3.2.4. Let Q be the quiver with representations X and Y as seen in Example ???. Then if there is a morphism $\theta : X \rightarrow Y$ its linear maps $\theta_i : X_i \rightarrow Y_i$ must be such that the following squares commute.

$$\begin{array}{ccc} k & \xleftarrow{1} & k \\ \downarrow \theta_1 & & \downarrow \theta_2 \\ k & \xleftarrow{1} & k \end{array} \quad \begin{array}{ccc} k & \xrightarrow{1} & k \\ \downarrow \theta_2 & & \downarrow \theta_3 \\ k & \xrightarrow{\quad} & 0 \end{array}$$

Hence we must have $\theta_2 = \theta_1$ and $\theta_3 = 0$. Hence $\text{Hom}(X, Y)$ is one-dimensional. Similarly, there are commutative squares showing that if we have a morphism $\psi : Y \rightarrow X$ with linear maps $\psi_i : Y_i \rightarrow X_i$ we must have $\psi_1 = \psi_2$ and $\psi_2 = 0$. Hence $\text{Hom}(Y, X) = 0$.

Theorem 3.2.5. Let Q be a quiver and k a field. Then the category of representations of Q is equivalent to the left modules of kQ .

Proof. First we give the construction.

If χ is a left kQ -module, we define a representation $X = (\{X_i\}, \{X_\rho\})$ of Q with $X_i = e_i \chi$ and $X_\rho : X_{s(\rho)} \rightarrow X_{t(\rho)}$, $x \mapsto e_{t(\rho)} \rho(x)$. If X is a representation of Q we define a left kQ -module χ via: Set $\chi = \bigoplus_{i=1}^n X_i$. Let $\epsilon_i : X_i \rightarrow \chi$ and $\pi_i : \chi \rightarrow X_i$ be the canonical maps. We then define the action of $\rho \in kQ$ on χ for $\rho \in Q_1$ to be as the linear map $X_\rho : X_{s(\rho)} \rightarrow X_{t(\rho)}$ on $X_{s(\rho)}$ and as zero on the all other X_i and so have,

$$\rho_1 \dots \rho_m x = \epsilon_{t(\rho_m)} X_{\rho_m} \pi_{s_{\rho_m}}(x).$$

We then define the action of $e_i \in kQ$ on χ as the projection of χ onto the summand X_i and so have,

$$e_i x = \epsilon_i \pi_i(x).$$

As Crawley-Boevey notes it is straightforward to check that these are inverses and the morphisms behave, so we will not prove it here. \square

Remark 3.2.6. We can now ignore the distinction between left modules and their corresponding representation.

Example 3.2.7. Once again consider the quiver Q and representation Y from Example ??. The corresponding left module will be $\chi = k \oplus k \oplus 0$ with the action $e_1(x_1, x_2, 0) = (x_1, 0, 0)$, $e_2(x_1, x_2, 0) = (0, x_2, 0)$ and $\alpha(x_1, x_2, 0) = \epsilon_1 Y_\alpha \pi_2(x_1, x_2, 0) = (x_2, 0, 0)$.

Definition 3.2.8. Let A be an algebra. Then A is said to be *hereditary* if every submodule of a projective module is projective.

The following theorem leads to some interesting result showing that path algebras are hereditary. It was taken almost word for word from [2] and [11]

Theorem 3.2.9. (*Standard Resolution*)

Let $A = kQ$. If X is a left A -module, there is an exact sequence,

$$0 \rightarrow \bigoplus_{\rho \in Q_1} Ae_{t(\rho)} \otimes_k e_{s(\rho)} X \xrightarrow{f} \bigoplus_{i \in Q_0} Ae_i \otimes_k e_i X \xrightarrow{g} X \rightarrow 0,$$

where $g(a \otimes x) = ax$ for $a \in Ae_i$, $x \in e_i X$ and $f(a \otimes x) = a\rho \otimes x - a \otimes \rho x$ for $a \in Ae_{t(\rho)}$ and $x \in e_{s(\rho)} X$.

Proof. A direct calculation shows that $gf = 0$ and so $\text{im}(f) \subseteq \ker(g)$. Suppose that there is some element $x \in X$ such that $x \notin \text{im}(g)$, but X is a left module of A and so $x = ax'$ for some $x' \in X$ and $x' \in e_i X$ for some vertex i . Hence $x = ax' = g(a \otimes x')$, a contradiction. Thus g is onto. Now all that needs to be show is that f is injective and $\ker(g) \subseteq \text{im}(f)$.

If $\xi \in \bigoplus_{i \in Q_0} Ae_i \otimes_k e_i X$ then it can be written uniquely as,

$$\xi = \sum_{i \in Q_0} \sum_{\substack{\text{paths } a \text{ with} \\ s(a)=i}} a \otimes x_a,$$

with $x_a \in e_{s(a)} X$ almost all zero. Define $\text{degree}(\xi) = \text{length of the longest path } a \text{ with } x_a \neq 0$. If a is a nontrivial path with $s(a) = i$, then we can express it as a product of $a = a'\rho$ with ρ an arrow with $s(\rho) = i$, and a' another path. Viewing $a' \otimes x_a$ as an element of $Ae_{t(\rho)} \otimes_k e_i X$, we have,

$$f(a' \otimes x_a) = a \otimes x_a - a' \otimes \rho x_a.$$

We claim that $\xi + \text{im}(f)$ always contains an element of degree zero. Namely if ξ have degree $d > 0$, then,

$$\xi - f\left(\sum_{i \in Q_0} \sum_{\substack{\text{paths } a \text{ with} \\ s(a)=i \text{ and length } d}} a' \otimes x_a\right)$$

has degree less than d and so the claim follows by induction.

Now to show $\text{im}(f) = \ker(g)$: If $\xi \in \ker(g)$, let $\xi' \in \xi + \text{im}(f)$ have degree zero. Then as $gf = 0$,

$$0 = g(\xi) = g(\xi') = g\left(\sum_{i \in Q_0} e_i \otimes x'_{e_i}\right) = \sum_{i \in Q_0} x'_{e_i}.$$

Now this belongs to $\bigoplus_{i \in Q_0} X_i$, so each term in the final sum must be zero.

Thus $\xi' = 0$, and the assertion follows.

To show that $\ker(f) = 0$, let $\zeta \in \ker(f)$ and write,

$$\zeta = \sum_{\rho \in Q_1} \sum_{\substack{\text{paths } a \text{ with} \\ s(a)=t(\rho)}} a \otimes x_{\rho,a},$$

where $x_{\rho,a} \in e_{s(\rho)}X$ and are almost all zero. Suppose $\zeta \neq 0$. Let a be a path of maximal length such that $x_{\rho,a} \neq 0$ for some path ρ . Then,

$$f(\zeta) = \sum_{\rho} \sum_a a\rho \otimes x_{\rho,a} - \sum_{\rho} \sum_a a \otimes \rho x_{\rho,a},$$

and so as a was chosen to be of maximal length such that $x_{\rho,a}$ is nonzero, the only term of $f(\zeta)$ in which it $a\rho$ appears in the first factor is $a\rho \otimes x_{\rho,a}$. Since $x_{\rho,a}$ is nonzero, we have $f(\zeta) \neq 0$. A contradiction and so $\zeta = 0$. Thus $\ker(f) = 0$. \square

The following consequences of Theorem ?? are from [2] and [11].

Corollary 3.2.10. *If X is a left A -module, then $\text{pd}(X) \leq 1$.*

Proof. If f and g are A -module maps and $Ae_i \otimes V$ is isomorphic to the direct sum of $\dim V$ copies of Ae_i , so is a projective left A -module. Thus the standard resolution in Theorem ?? is a projective resolution for X . \square

Corollary 3.2.11. *A path algebra $A = kQ$ is hereditary.*

Proof. Let X, P be left A -modules with P projective and X a submodule of P . First note that $\text{Ext}^1(X, Y) \cong \text{Ext}^2(P/X, Y)$ for any Y . Then P/X is a left A -module and so by Corollary ??, $\text{pd}(P/X) \leq 1$. So for any Y , $\text{Ext}^n(P/X, Y) = 0$ for $n \geq 2$, in particular, $\text{Ext}^2(P/X, Y) = 0$. Thus $\text{Ext}^1(X, Y) = 0$ and X is projective. \square

Chapter 4

Auslander-Reiten Theory

This chapter will discuss some of the notions and results introduced by Maurice Auslander and Idun Reiten in 1975 and subsequent developments of their theories; including the Auslander-Reiten translate, almost split sequences and the Auslander-Reiten quiver. The main sources for this chapter will be [10], [11] and [14], however, we will primarily be following [10] as we prefer Crawley-Boevey's approach with source and sink maps. Throughout this chapter, k is an algebraically closed field and A is a finite dimensional k -algebra.

For every finite-dimensional algebra there exists an Auslander-Reiten quiver, which can be viewed as an approximation to the module category of the algebra. Auslander-Reiten quivers are important as they can be easily computed and give a remarkable insight into the structure of the module category of an algebra. For example, the Auslander-Reiten quiver of an Artin algebra has a vertex for each indecomposable module and an arrow between vertices if there exists an irreducible morphism between the corresponding modules. [13]

4.1 Irreducible Maps

In order to obtain a picture of the module category, [11] notes that it is best to remove those morphisms which are simply compositions of other morphisms, and so retain those morphisms which can not be decomposed any further. Thus we want to find a suitable definition for a map which can not be broken down as the composition of other maps. Vale acknowledges that a first guess at such a definition would be:

Wrong Definition. *A map $f : X \rightarrow Y$ is irreducible if f is not an isomorphism and if $f = gh$ then either g or h is an isomorphism.*

However, every $f : X \rightarrow Y$ can be factorised as,

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow \text{nat} & \nearrow (f \ 0) \\ & X \oplus Z & \end{array}$$

where Z is arbitrary. Also, every $f : X \rightarrow Y$ could be factorised,

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow \scriptstyle \begin{pmatrix} f \\ 0 \end{pmatrix} & \nearrow \scriptstyle \pi \\ & Y \oplus Z & \end{array}$$

where Z is once again arbitrary. Thus, the set of morphisms described in Wrong Definition is empty and so we must find a definition which rules out the two above factorisations.

Definition 4.1.1. If $f : X \rightarrow Y$ then,

- f is *split mono* if there exists $h : Y \rightarrow X$ such that $hf = id_X$, i.e., the inclusion of a direct summand.
- f is *split epi* if there exists $g : Y \rightarrow X$ such that $fg = id_Y$, i.e., the projection onto a direct summand.

Remark 4.1.2. Notice that these definitions are equivalent to f being a section or a retraction respectively.

Definition 4.1.3. • If X is indecomposable then $f : X \rightarrow Y$ is *irreducible* if it is not split mono and if $f = hg$ then either g is split mono or h is split epi.

- If Y is indecomposable then $f : X \rightarrow Y$ is *irreducible* if it is not split mono and if $f = hg$ then either g is split mono or h is split epi.

Remark 4.1.4. If both X and Y are indecomposable the two notions of the irreducibility of $f : X \rightarrow Y$ agree. In this report we will follow [10] in not defining irreducible maps where X, Y decomposable.

Proposition 4.1.5. *An irreducible map $f : X \rightarrow Y$ is mono or epi.*

Proof. If not then we can have,

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow \scriptstyle g & \nearrow \scriptstyle h \\ & im(f) & \end{array}$$

and so f factors through $im(f)$. However, as f is not mono, g can not be split mono and similarly, if as f is not split epi then h can not be split epi. \square

Proposition 4.1.6. (i) *The cokernel of an irreducible monomorphism is indecomposable.*

(ii) *The kernel of an irreducible epimorphism is indecomposable.*

Proof. We will not prove these in this report, but proofs can be found in [14]. \square

Proposition 4.1.7. (i) Suppose X is indecomposable and $X \rightarrow E$ is a source map. Then the irreducible maps starting at X are the compositions $X \rightarrow E \rightarrow Y$ with $E \rightarrow Y$ split epi.

(ii) Suppose Y is indecomposable and $F \rightarrow Y$ is a sink map. Then the irreducible maps ending at Y are the compositions $X \rightarrow F \rightarrow Y$ with $X \rightarrow F$ split mono.

Proof. (i) Firstly, we show $E \rightarrow Y$ is split epi: If $f : X \rightarrow Y$ is irreducible it factors through the source map $X \rightarrow E$ such that,

$$X \xrightarrow{g} E \xrightarrow{h} Y,$$

with either $g : X \rightarrow E$ split mono or $h : E \rightarrow Y$ split epi. However, $g : X \rightarrow E$ is a source map for X and so by definition g is irreducible, hence is not split mono. Thus, $h : E \rightarrow Y$ is split epi.

To show a composition is irreducible, show that if $\begin{pmatrix} f \\ f' \end{pmatrix} : X \rightarrow Y \oplus U$ is irreducible then so is $f : X \rightarrow Y$. Namely, if f factors through V then $\begin{pmatrix} f \\ f' \end{pmatrix}$ factors through $V \oplus U$.

(ii) The dual of (i). □

Definition 4.1.8. Let X, Y be A -modules. Then we define,

$$\text{rad}(X, Y) = \{f : X \rightarrow Y : \forall g : Y \rightarrow X, id_X - gf \text{ is an isomorphism}\}.$$

Remark 4.1.9. Note [10] gives a different definition of $\text{rad}(X, Y)$ is given that the one above from [11]. In [10] Crawley-Boevey sets X, Y indecomposable modules and defines $\text{rad}(X, Y)$;

$$\text{rad}(X, Y) = \{f : X \rightarrow Y : f \text{ is not an isomorphism}\}.$$

The following proposition from [11] shows that these two sets are in fact equivalent when X, Y indecomposable.

Lemma 4.1.10. If X and Y are indecomposable then f is not an isomorphism if and only if $f \in \text{rad}(X, Y)$.

Proof. \Leftarrow : If f is an isomorphism and so has an inverse $f^{-1} : Y \rightarrow X$ then $id_X - ff^{-1} = 0$. Hence, $f \notin \text{rad}(X, Y)$. \Rightarrow : If f is an isomorphism then let $g : Y \rightarrow X$. Now first show that gf is not an isomorphism. Suppose to the contrary that gf is an isomorphism and let $e = f(gf)^{-1}g \in \text{End}(Y)$. Then,

$$\begin{aligned} e^2 &= (f(gf)^{-1}g)(f(gf)^{-1}g), \\ &= f(gf)^{-1}gf(gf)^{-1}g, \\ &= f(gf)^{-1}g, \\ &= e, \end{aligned}$$

and so e is idempotent and so not nilpotent. By Fitting's Lemma, e is an isomorphism, but $e^2 = e$ so $e = id_Y$. Therefore, $f(gf)^{-1}g = id_Y$ and so $(gf)^{-1}g$ is an inverse to f , and so a contradiction to f not an isomorphism. Thus, gf is not an isomorphism. By Fitting's Lemma, if $gf \in \text{End}(X)$ is not an isomorphism, then it must be nilpotent. So $id_X - gf$ has an inverse and so is an isomorphism. Thus, $f \in \text{rad}(X, Y)$. □

From now on we will use the notation $rad(X, Y)$ to refer either of these sets. In addition, it is proven in [11] that $rad(X, Y)$ is a vector space.

Definition 4.1.11. If X and Y are A -modules we define $rad^2(X, Y)$ as the span of all map $hg : X \rightarrow Y$ where $g : X \rightarrow Z$, $h : Z \rightarrow Y$ for some Z and $g \in rad(X, Z)$, $h \in rad(Z, Y)$.

Lemma 4.1.12. Let X, Y indecomposable modules and define a map $f : X \rightarrow Y$, then, $f \in rad^2(X, Y)$ if and only if $f = hg$ with g not split mono and h not split epi.

Proof. Let $f : X \rightarrow Y$ with X, Y indecomposable.

\Rightarrow : Observe that there is no requirement that Z is an indecomposable module and so set $Z = \bigoplus_i^n Z_i$ where the Z_i are indecomposable. Then if $f = gh$ we have,

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow \quad \nearrow & \\ \begin{pmatrix} h_1 \\ \vdots \\ h_n \end{pmatrix} & Z_1 \oplus Z_2 & \begin{pmatrix} g_1 & \dots & g_n \end{pmatrix} \end{array}$$

with $h_i : X \rightarrow Z_i$ and $g_i : Z_i \rightarrow Y$ with f a finite linear combination of $g_i h_i$. We want to show:

- (i) $h_i \in rad(X, Z_i)$ for all i if and only if h is not a split mono.
- (ii) $g_i \in rad(Z_i, Y)$ for all i if and only if g is not split epi.

Proof of (i): As X is indecomposable $h_i \in rad(X, Z)$ implies that h_i is not an isomorphism. Hence, (i) becomes: all the h_i are non-isomorphisms if and only if h is not a split mono. But this is equivalent to proving (*) some h_i is an isomorphism if and only if h is split mono.

(*) \Leftarrow : Suppose for some i , h_i is an isomorphism then h_i has some inverse, h_i^{-1} say, such that,

$$\begin{array}{ccccc} X & \xrightarrow{h = \begin{pmatrix} h_1 \\ \vdots \\ h_n \end{pmatrix}} & Z_1 \oplus \dots \oplus Z_n & \xrightarrow{(0 \dots 0 h_i^{-1} 0 \dots 0)} & X \\ & \searrow & & \nearrow & \\ & & id_X & & \end{array}$$

Hence h is split mono.

(*) \Rightarrow : If h is split mono then there exists some r such that,

$$\begin{array}{ccccc} X & \xrightarrow{h = \begin{pmatrix} h_1 \\ \vdots \\ h_n \end{pmatrix}} & Z_1 \oplus \dots \oplus Z_n & \xrightarrow{(r_1 \dots r_n)} & X \\ & \searrow & & \nearrow & \\ & & id_X & & \end{array}$$

and so $\sum_i^n r_i h_i = id_X$. But X is indecomposable so $End(X)$ is a local ring and so as $\sum_i^n r_i h_i = id_X$ we must have some $r_i h_i$ invertible. Say the inverse of $r_i h_i$

is s , then, $(sr_i)h = id_X$ and so h_i is split mono so it embeds in X as a direct summand of Z_i . But the Z_i are indecomposable, thus h_i is an isomorphism. The proof of (ii) is dual. \square

The above result makes the next theorem very clear.

Theorem 4.1.13. *Let X, Y be indecomposable. Then $f : X \rightarrow Y$ is irreducible if and only if $f \in rad(X, Y) \setminus rad^2(X, Y)$, where \setminus denotes the set difference.*

Proof. \Rightarrow : Suppose $f : X \rightarrow Y$ is irreducible. Then it is not an isomorphism and so $f \in rad(X, Y)$ by Lemma 4.1.10. Also as f is irreducible, if $f = hg$ then either g is split mono or h is split epi and so by Lemma 4.1.12 $f \notin rad^2(X, Y)$. Thus $f \in rad(X, Y) \setminus rad^2(X, Y)$.

\Leftarrow : Suppose $f \in rad(X, Y) \setminus rad^2(X, Y)$. Since X, Y indecomposable and f not an isomorphism f cannot be split mono or split epi. If $f = hg$ then as $f \notin rad^2(X, Y)$ we must have either g is split mono or h split epi. Thus, f is irreducible. \square

Definition 4.1.14. If X, Y indecomposable modules then we define $irr(X, Y) = rad(X, Y) \setminus rad^2(X, Y)$.

4.2 Almost Split Sequences

Definition 4.2.1. • A map $f : L \rightarrow M$ is called *left minimal* if for all $h \in End(M)$ with $hf = f$, we have h is an automorphism.

- A map $g : M \rightarrow N$ is called *right minimal* if for all $h \in End(M)$ with $gh = g$, we have h is an automorphism.

Definition 4.2.2. A map $f : L \rightarrow M$ is called *left almost-split* if f is not split mono and if,

$$\begin{array}{ccc} L & \xrightarrow{f} & M \\ u \downarrow & \exists u' \swarrow & \nearrow \\ & Z & \end{array} \quad (4.1)$$

with u not split mono, then there exists a map $u' : M \rightarrow Z$ such that 4.1 commutes, i.e. any map $u : L \rightarrow Z$ which is not split mono factors through f .

Definition 4.2.3. A map $g : M \rightarrow N$ is called *right almost-split* if g is not split epi and if,

$$\begin{array}{ccc} & & Z \\ \exists v' \swarrow & & \downarrow v \\ M & \xrightarrow{g} & N \end{array} \quad (4.2)$$

with v not split epi, then there exists $v' : F \rightarrow Z$ such that 4.2 commutes, i.e. any map $v : F \rightarrow N$ which is not split epi factors through g .

Below we define source and sink maps differently as to [10], however, we will later see that these definitions are equivalent.

Definition 4.2.4. • A map $f : L \rightarrow M$ is *left minimal almost-split* if it is both left minimal and left almost-split. Then the map $f : L \rightarrow M$ is said to be a *source map* for L .

• A map $g : M \rightarrow N$ is *right minimal almost-split* if it is both right minimal and right almost-split. Then the map $g : M \rightarrow N$ is said to be a *sink map* for N .

Clearly, as noted in [14], each "right-hand" notion is the dual of the corresponding "left hand" notion. Next is a Proposition from [14] showing that left or right minimal almost-split maps uniquely determine their targets, or sources, respectively.

Proposition 4.2.5. (i) *If the maps $f : L \rightarrow M$ and $f' : L \rightarrow M'$ are sink maps for L , then there exists an isomorphism $h : M \rightarrow M'$ such that $f' = hf$.*

(ii) *If the maps $g : M \rightarrow N$ and $g' : M' \rightarrow N$ are source maps for N , then there exists an isomorphism $h : M \rightarrow M'$ such that $g = g'h$.*

Proof. As (i) was proven in [14], and (ii) left, here we shall only prove (ii): As g and g' are right almost-split there exist $h : M' \rightarrow M$ and $h' : M \rightarrow M'$ such that,

$$\begin{array}{ccc} & & M' \\ & \nearrow \exists h & \uparrow \\ M & \xrightarrow{g} & N \end{array}$$

such that $g = g'h$ and $g' = gh'$. Hence, $g = gh'h$ and $g' = gh'h'$. Since g and g' are right minimal, $h'h$ and hh' are automorphisms and consequently h is an isomorphism. \square

The following result is from [11] and [14] and displays that almost-split maps are closely related to indecomposable modules.

Lemma 4.2.6. (i) *If $f : L \rightarrow M$ is left almost-split then L is indecomposable.*

(ii) *If $g : M \rightarrow N$ is right almost-split then N is indecomposable.*

Proof. We will follow [11] here and only prove the result for (ii) as the proof for (i) is the dual argument.

Suppose $g : M \rightarrow N$ is right almost-split and $N = N_1 \oplus N_2$ with both N_1, N_2 nonzero. Then the insertion maps $\iota_i : N_i \hookrightarrow N_1 \oplus N_2$ are not split epi, and so there exists $v_1 : N_1 \rightarrow N$ with $gv_1 = \iota_1$ and $v_2 : N_2 \rightarrow N$ with $gv_2 = \iota_2$. Then $g(v_1 + v_2) = \iota_1 + \iota_2 = id_N$, contradicting g not split epi. \square

Lemma 4.2.7. *If $f : L \rightarrow M$ is a sink or source map then f is irreducible.*

Proof. Once again as the proof for f sink map for M is given in [11] we will prove the result when f is source map for L .

As $f : L \rightarrow M$ is left almost-split Lemma gives L indecomposable thus to prove f is irreducible we must show f is not split mono and that if $f = f_1 f_2$ then either f_2 is split mono or f_1 is split epi. By definition f cannot be split mono so is not an isomorphism and as L is indecomposable it cannot be split epi either. Now suppose $f = f_1 f_2$,

$$\begin{array}{ccc} L & \xrightarrow{\quad} & M \\ & \searrow f_2 \quad \nearrow f_1 & \\ & N & \end{array}$$

with f_2 not split mono. As f is left almost-split there exists $u : M \rightarrow N$ such that $uf = f_2$ and then $f_1 u f = f_1 f_2 = f$. At the same time f is left minimal and so $f_1 u : M \rightarrow M$ is an automorphism. Thus, f_1 is split epi. \square

The following proposition is the final result needed to show that the definition given for source and sink maps in this report is equivalent to the one given in [10].

Proposition 4.2.8. *Let L, N be indecomposable modules.*

- (i) *If the map $f : L \rightarrow M$ is irreducible then it is left minimal.*
- (ii) *If the map $g : M \rightarrow N$ is irreducible then it is right minimal.*

Proof. (i) If we have some map $h : M \rightarrow M$ such that $hf = f$,

$$\begin{array}{ccc} L & \xrightarrow{\quad} & M \\ & \searrow f \quad \nearrow h & \\ & M & \end{array}$$

then as f is irreducible then either f is split mono or h is split epi. However, f cannot be split mono by definition, hence h is split epi. Then there exists some $h' : M \rightarrow M$ such that $hh' = id_M$ and so h is an automorphism.

- (ii) This is the dual case. \square

Lemma 4.2.9. (i) *If X is an indecomposable projective module then X has a unique maximal proper submodule M and $f : M \hookrightarrow X$ is a sink map for X .*

- (ii) *If Y is an indecomposable injective then Y has a unique simple submodule S and $g : Y \twoheadrightarrow Y/S$ is a source map for Y .*

Proof. (i) Suppose to the contrary X has two distinct maximal proper submodules M, M' then $M \oplus M' = X$ so $M \oplus M' \twoheadrightarrow X$, and so X is a summand of $M \oplus M'$, a contradiction by Krull-Schmidt as X is indecomposable. If $f : M \rightarrow X$ factors as $f = hh'$ then $im(h) = M$ or $im(h) = X$ and so h' is

split mono or h is split epi respectively. If $\phi : Z \rightarrow X$ is not split epi, then it is not epi, and so the image is contained in M , hence ϕ factors through f . Thus $f : M \hookrightarrow X$ is a sink map for X .

- (ii) Suppose to the contrary that Y has two distinct simple submodules S and T then $Y/S \oplus Y/T = X$ so $X/Y \oplus Y/T \twoheadrightarrow Y$, and so X is a summand of $Y/S \oplus Y/T$, once again a contraction by Krull-Schmidt as Y is indecomposable. To show the map $g : Y \rightarrow Y/S$ is irreducible: Firstly as g is not mono it can not be split mono and if $g = h'h$ then either $\ker(h) = 0$ or $\ker(h) = S$ as $\ker(h'h) = \ker(f) = S$ and $\ker(h) \subseteq \ker(h'h)$. If $\ker(h) = 0$ then h is injective and so, since Y is injective, h is split mono. On the other hand, if $\ker(h) = S$, then we have,

$$\begin{array}{ccc} Y & \xrightarrow{g} & Y/S \\ & \searrow g & \nearrow h' \\ & Y/S & \\ & \searrow \hat{h} & \\ & W & \end{array}$$

h (curved arrow from Y to W)

and so $g = h\hat{h}g$ and so $(id_{Y/S} - h'\hat{h})g = 0$ but g is surjective so $id_{Y/S} = h'\hat{h}$ and so h is split epi. Now if $\theta : Y \rightarrow Z$ is not split mono then the kernel is a nonzero subset of S , hence θ factors through g . Thus $Y \twoheadrightarrow Y/S$ is a source map for Y .

□

Corollary 4.2.10. (i) *If X is an indecomposable projective module then X has a sink map $f : \text{rad}(X) \rightarrow X$.*

- (ii) *If Y is an indecomposable injective module then Y has a source map $g : Y \rightarrow Y/\text{soc}(Y)$.*

Proof. Recall that $\text{rad}(M) = \bigcap \{N : N \text{ is a maximal submodule of } M\}$ and $\text{soc}(M) = \sum \{S : S \text{ is a simple submodule of } M\}$. Then Lemma ?? gives the result with M substituted with X and Y respectively. □

In this report an Auslander-Reiten sequence will simply be another name for an almost-split sequence, as in the literature there seemed little basis to follow Vale and define them separately. Moreover, it was felt Vale's approach causes much unnecessary confusion.

Definition 4.2.11. A short exact sequence,

$$0 \rightarrow L \xrightarrow{f} M \xrightarrow{g} N \rightarrow 0,$$

is called an *almost split sequence* or *Auslander-Reiten sequence* if f is a source map for L and g is a sink map for N .

The following discussion of almost-split sequences is made in [14].

Remark 4.2.12. It follows from Lemma 4.2 that if such a sequence exists then L and N are indecomposable. Also as almost-split sequences are never split, L cannot be injective and N cannot be projective as this would contradict Lemma ?? and Lemma 2.4.3 respectively.

4.3 Auslander-Reiten Translate

The topic of this section is the Auslander-Reiten translate. We first present some properties of the standard duality and Nakayama functor from [2] without proof.

Definition 4.3.1. A contravariant functor $D : \mathcal{C} \rightarrow \mathcal{D}$ that is an equivalence of categories is called a *duality*. The standard duality is defined $D(-) = \text{Hom}_k(-, k) : \text{mod} A \rightarrow \text{mod} A^{op}$, between the category $\text{mod} A$ of finite dimensional right A -modules and the category $\text{mod} A^{op}$ of finite dimensional left A -modules.

Remark 4.3.2. The following are properties of the standard duality from [2]:

- (i) If X is a left or right A -module, then $DX = \text{Hom}_k(X, k)$, $\text{Hom}(X, A)$ and $\text{Ext}^1(X, A)$ are all A -modules on the right or left side respectively.
- (ii) $D(-)$ is duality between left and right A -modules.
- (iii) $D(-)$ gives a duality between injective left modules and projective right modules.
- (iv) $\text{Hom}(-, A)$ gives duality between projective left modules and projective right modules.

Definition 4.3.3. The *Nakayama functor* $\nu(-) = D\text{Hom}(-, A)$ gives an equivalence from projective left A -modules to projective right A -modules. The inverse functor is $\nu^-(-) = \text{Hom}(D(-), A) \cong \text{Hom}(DA, -)$.

Remark 4.3.4. For X, P left A -modules, P projective, $\text{Hom}(X, \nu P) \cong D\text{Hom}(P, X)$.

Now to start defining the Auslander-Reiten translate.

Definition 4.3.5. If M is a module then let (P_0, ϵ) be a projective cover of M and (P_1, ϕ) a projective cover of $\ker(\epsilon)$. Then the exact sequence,

$$P_1 \rightarrow P_0 \xrightarrow{\epsilon} M \rightarrow 0,$$

is called a *minimal presentation* of M .

Definition 4.3.6. Given a left A -module M , take a minimal presentation $P_1 \rightarrow P_0 \rightarrow M \rightarrow 0$ and let $\beta : P_1 \rightarrow P_0$ be the map in this sequence. Apply $\text{Hom}_A(-, A)$ to obtain a map of right A -modules,

$$\beta^* : \text{Hom}_A(P_0, A) \rightarrow \text{Hom}_A(P_1, A).$$

Then the *transpose* of M is defined to be $\text{Tr}(M) := \text{cok}(\beta^*)$.

Definition 4.3.7. The *Auslander-Reiten translates* of M are defined to be $\tau M := D\text{Tr}(M)$ and $\tau^{-1}M := \text{Tr}D(M)$.

Example 4.3.8. If the algebra A is hereditary then we have the case we see in [2] and [10]. Let $P_1 \xrightarrow{\beta} P_0 \rightarrow M \rightarrow 0$ be a minimal presentation of M . As A is hereditary we have $\beta : P_1 \rightarrow P_0$ injective and so we in fact have the short exact

sequence $0 \rightarrow P_1 \hookrightarrow P_0 \twoheadrightarrow M \rightarrow 0$. Then applying $\text{Hom}_A(-, A)$ and writing out the long exact sequence we obtain,

$$0 \rightarrow \text{Hom}_A(M, A) \rightarrow \text{Hom}_A(P_0, A) \xrightarrow{\beta^*} \text{Hom}_A(P_1, A) \xrightarrow{\delta} \text{Ext}^1(M, A) \rightarrow 0$$

as P_0 is projective. Hence,

$$\text{coker}(\beta^*) = \frac{\text{Hom}(P_1, A)}{\text{im}(\beta^*)} = \frac{\text{Hom}(P_1, A)}{\text{ker}(\delta)} \cong \text{Ext}^1(M, A),$$

as δ is surjective and so we can use the first isomorphism theorem. Thus, $\text{Tr}(M) = \text{Ext}^1(M, A)$ and so we have $\tau M = \text{DExt}^1(M, A)$.

Theorem 4.3.9. *There are bijections,*

$$\left\{ \begin{array}{l} \text{non-projective} \\ \text{indecomposables} \end{array} \right\} \begin{array}{c} \xleftarrow{\tau} \\ \xrightarrow{\tau^{-1}} \end{array} \left\{ \begin{array}{l} \text{non-injective} \\ \text{indecomposables} \end{array} \right\}$$

such that if X is non-projective indecomposable there is an exact sequence,

$$\xi : 0 \rightarrow X \rightarrow E \rightarrow \tau X \rightarrow 0,$$

with ξ an almost split sequence. Also, if Y is non-injective indecomposable there is an exact sequence,

$$\xi' : 0 \rightarrow \tau^{-1}Y \rightarrow F \rightarrow Y \rightarrow 0,$$

with ξ' an almost split sequence.

We will only prove this theorem in the case that A is hereditary as in [10] using results from [2]. Recall that when A is hereditary $\tau = \text{DExt}^1(-, A)$.

Lemma 4.3.10. *Let A be hereditary. Then, $\text{Hom}(Y, \tau X) \cong \text{DExt}^1(X, Y) \cong \text{Hom}(\tau^{-1}Y, X)$.*

Proof. Let $0 \rightarrow P_1 \rightarrow P_0 \rightarrow X \rightarrow 0$ be a projective resolution of X . Then since A is hereditary, we have the long exact sequence,

$$0 \rightarrow \text{Hom}(X, A) \rightarrow \text{Hom}(P_0, A) \rightarrow \text{Hom}(P_1, A) \rightarrow \text{Ext}^1(X, A) \rightarrow \text{Ext}^1(P_0, A) \rightarrow \dots$$

Then the sequence,

$$\tau P_0 \rightarrow \tau X \rightarrow \nu P_1 \rightarrow \nu P_0,$$

is exact and $\tau P_0 = \text{DExt}^1(P_0, A) = 0$ because P_0 is projective. So we have a commutative diagram with exact rows,

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Hom}(Y, \tau X) & \longrightarrow & \text{Hom}(Y, \nu P_1) & \longrightarrow & \text{Hom}(Y, \nu P_0) \\ & & & & \parallel & & \parallel \\ 0 & \longrightarrow & \text{DExt}^1(X, Y) & \longrightarrow & \text{DHom}(P_1, Y) & \longrightarrow & \text{DHom}(P_0, Y) \end{array}$$

Hence $\text{Hom}(Y, \tau X) \cong \text{DExt}^1(X, Y)$. The other result is dual. \square

Lemma 4.3.11. *Let X be indecomposable and A hereditary.*

- (i) *If X is non-projective then $\text{Hom}(X, P) = 0$ for P projective and $\tau^{-1}\tau X \cong X$.*
- (ii) *If X is non-injective then $\text{Hom}(I, X) = 0$ for I injective and $\tau\tau^{-1}X \cong X$.*

Proof. As the proof of (i) is given in [2] we will only prove (ii).

If $\psi : I \rightarrow X$ is non-zero then $I/\ker(\psi)$ is injective since A is hereditary. Now $I/\ker(\psi) \rightarrow X$ is mono, so $I/\ker(\psi)$ is a direct summand of X and as X is indecomposable $X \cong I/\ker(\psi)$. However, X is non-injective so a contradiction. Let $0 \rightarrow X \rightarrow I^0 \rightarrow I^1 \rightarrow 0$ be an injective resolution of X . Now

$$0 \rightarrow \nu^{-1}X \rightarrow \nu^{-1}I^0 \rightarrow \nu^{-1}I^1 \rightarrow \tau^{-1}X \rightarrow 0,$$

is exact and $\nu^{-1}X = 0$ since $\text{Hom}(A, X) = 0$. Thus we have a commutative diagram,

$$\begin{array}{ccccccc} \tau\nu^{-1}I^1 & \longrightarrow & \tau\tau^{-1}X & \longrightarrow & \nu\nu^{-1}I^0 & \longrightarrow & \nu\nu^{-1}I^1 \\ & & & & \parallel & & \parallel \\ 0 & \longrightarrow & X & \longrightarrow & I^0 & \longrightarrow & I^1 \end{array}$$

with exact rows. Since $\nu^{-1}I^1$ is projective we have $\tau\nu^{-1}I^1 = 0$ and thus $\tau\tau^{-1}X \cong X$. \square

Lemma 4.3.12. *Let A be a hereditary algebra. The Auslander-Reiten translates τ and τ^{-1} give inverse bijections:*

$$\left\{ \begin{array}{l} \text{non-projective} \\ \text{indecomposables} \end{array} \right\} \xrightleftharpoons[\tau^{-1}]{\tau} \left\{ \begin{array}{l} \text{non-injective} \\ \text{indecomposables} \end{array} \right\}$$

Proof. As the result is prove for τ in [2] we only prove it for τ^{-1} .

Let Y be a non-injective indecomposable and write $\tau^{-1}Y$ as a direct sum of indecomposables, say $\tau^{-1}Y = \bigoplus_{i=1}^r X_i$. Each X_i is non-projective since otherwise $\text{Hom}(\tau^{-1}Y, X_i) \cong \text{DExt}^1(X_i, Y) = 0$ by Lemma 4.3.10. By Lemma 4.3.11 (i) it follows that for each X_i , $\tau(X_i) \neq 0$. By Lemma 4.3.11 (ii) we have $Y \cong \tau\tau^{-1}Y \cong \bigoplus_{i=1}^r \tau X_i$ and since Y is indecomposable we must have $r = 1$. Thus $\tau^{-1}Y$ is a non-injective indecomposable. \square

We now have all the results necessary to prove Theorem 4.3.9.

Proof. (of Theorem 4.3.9 From Lemma 4.3.12 we can see that the translation functors induce such bijections. Now we will show that such an exact sequence ξ exists.

Define a linear map $\phi : \text{End}(X) \rightarrow k$ via $\phi(\text{rad}(\text{End}(X))) = 0$, $\phi(1_X) = 1$. Let $\xi \in \text{Ext}^1(X, \tau X) \cong \text{DEnd}(X)$ correspond to ϕ . Since $\xi \neq 0$, it follows that ξ is not split and so g is not split epi and f is not split mono.

If $h : Z \rightarrow X$ is not split epi, then it factors through g , for h gives a commutative square,

$$\begin{array}{ccc} \text{Ext}^1(X, \tau X) & \longrightarrow & \text{Ext}^1(Z, \tau X) \\ \parallel & & \parallel \\ & \text{Lemma 4.3.10} & \\ \text{DHom}(X, X) & \longrightarrow & \text{DHom}(X, Z) \end{array}$$

and the bottom map send $\phi : \text{End}(X) \rightarrow k$ to 0 since if $\alpha \in \text{Hom}(X, Z)$ then $\phi(h\alpha) = 0$. Thus the pullback of ξ splits. Now g is irreducible: Suppose to the contrary that g factors as $hs : E \rightarrow Z \rightarrow X$ with s not split mono and h not split epi. Now $h = gt$ with $t : Z \rightarrow E$ and $g = (ts)$. We get a diagram,

$$\begin{array}{ccccccccc} 0 & \longrightarrow & \tau X & \xrightarrow{f} & E & \xrightarrow{g} & X & \longrightarrow & 0 \\ & & \downarrow \phi & & \downarrow ts & & \parallel & & \\ 0 & \longrightarrow & \tau X & \xrightarrow{f} & E & \xrightarrow{g} & X & \longrightarrow & 0 \end{array}$$

Since s is not split mono the map $ts \neq id_Z$ so not an isomorphism and so ϕ cannot be an isomorphism. Thus $\phi^r = 0$. Hence $(ts)^r$ factors through g , say $(ts)^r = ug$ for some $u : X \rightarrow E$. Now $gug = g$ and since g is epi we have $gu = id_X$. A contradiction since g is not split epi. Thus g is a sink map. Similarly f is a source map and so ξ is an almost split sequence.

The existence of ξ' follows by putting $X = \tau^{-1}Y$ into ξ . \square

Corollary 4.3.13. *Any indecomposable X has a source and sink map which are unique up to isomorphism.*

Proof. Uniqueness: This was proven for source maps in [10] and so we prove it here for sink maps. If $g : F \rightarrow X$ and $g' : F' \rightarrow X$ are sink maps for X then there is an isomorphism $F \rightarrow F'$ making a commutative triangle,

$$\begin{array}{ccc} & X & \\ g \nearrow & & \nwarrow g' \\ F & \xrightarrow{\quad} & F' \end{array}$$

and this follows from the definition as any map $Z \rightarrow X$ which is not split epi must factor through both g and g' .

Existence: For both sink and source maps follows from Lemma 4.2.9 and Theorem 4.3.9. \square

4.4 Auslander-Reiten Quiver

In this section we bring together the results of the Chapter to finally define an Auslander-Reiten Quiver. We follow [10].

Theorem 4.4.1. *Let X, Y be indecomposable. The following numbers are equal.*

- (i) $\dim \text{irr}(X, Y)$.
- (ii) *The multiplicity of X as a summand of F with $f : F \rightarrow Y$ a sink map.*
- (iii) *The multiplicity of Y as a summand of E with $g : X \rightarrow E$ a source map.*

Proof. In [10] it was shown that (i)=(ii) so we will show (i)=(iii).

(i)=(iii): Let $\begin{pmatrix} g_0 \\ g_1 \\ \vdots \\ g_s \end{pmatrix} : X \rightarrow Z \oplus Y^s$ be a source map, with Z having no summand isomorphic to Y . Clearly, $g_i \in \text{rad}(X, Y)$ for $i \geq 1$. We show that g_1, \dots, g_s give a basis of $\text{irr}(X, Y)$.

Span: Say $\phi : X \rightarrow Y$ belongs to $\text{rad}(X, Y)$. Now ϕ factors through through source map, so we can write $\phi = \sum_i h_i g_i$. For $i \geq 1$ we have $h_i \in \text{End}(Y)$, so there are $\lambda_i \in k$ with $h_i - \lambda_i 1_Y \in \text{radEnd}(Y)$. Modulo $\text{rad}^2(X, Y)$ we have,

$$\phi = \sum h_i g_i = \sum_{i \geq 1} h_i g_i = \sum_{i \geq 1} (h_i - \lambda_i 1_Y) g_i + \sum_{i \geq 1} \lambda_i g_i = \sum_{i \geq 1} \lambda_i g_i.$$

Linearly independent: Say $\sum_{i \geq 1} \lambda_i g_i \in \text{rad}^2(X, Y)$ with not all $\lambda_i = 0$. The map $Z \oplus Y^s \rightarrow Y$, $\lambda_i y \rightarrow y$ is split epi, so the composition with the source map is irreduciblye. Contradiction. \square

Corollary 4.4.2. *If X is non-projectie, then $\dim \text{irr}(\tau X, Y) = \dim \text{irr}(Y, X)$.*

Proof. Have source map $\tau X \rightarrow E$ and sink map $E \rightarrow X$. \square

Remark 4.4.3. Crawley-Boevey notes in [10] that if we know the sources and sinks we can compute all of $\text{irr}(X, Y)$. Conversely, if we know all of $\text{irr}(X, Y)$ we recover sources and sinks. Namely, X has source and sink maps,

$$X \rightarrow \bigoplus_{Z \text{ indec}} Z^{\dim \text{irr}(X, Z)} \quad \& \quad \bigoplus_{Z \text{ indec}} Z^{\dim \text{irr}(Z, X)} \rightarrow X.$$

Definition 4.4.4. The *Aulander-Reiten quiver* Γ of A has;

- vertices Γ_0 the set of isoclasses $[X]$ of indecomposable modules, a possibly infinite set, and;
- arrows Γ_1 with the number of arrows from $[X]$ to $[Y]$ being $\dim \text{irr}(X, Y)$.

Definition 4.4.5. A *translation quiver* is a quiver Γ with subsets $\Gamma_p, \Gamma_i \subseteq \Gamma_0$ and a bijection $\tau : \Gamma_0 \setminus \Gamma_p \rightarrow \Gamma_0 \setminus \Gamma_i$ with the property that if $x, y \in \Gamma_0$ and $x \notin \Gamma_p$ then the number of arrows $\tau x \rightarrow y$ equal to the number of arrows $y \rightarrow x$.

Example 4.4.6. The Auslander-Reiten quiver becomes a translation quiver by defining:

- $\Gamma_p =$ the set of vertices $[X]$ with X projective.
- $\Gamma_i =$ the set of vertices $[X]$ with X injective.
- $\tau : \Gamma_0 \setminus \Gamma_p \rightarrow \Gamma_0 \setminus \Gamma_i$ given by $\tau[X] = [\tau X]$.

4.5 Computing Auslander-Reiten Quivers

In this section we aim to bring together the results of the Chapter to provide an informal method of computing the Auslander-Reiten quiver of a path algebra.

Theorem 4.5.1. *Let $A = kQ$ and X an indecomposable module of A , then:*

- (i) *X has a unique source map $X \rightarrow E$ and a unique sink map $X \rightarrow F$.*
- (ii) *If X is projective then its sink map is $\text{rad}(X) \rightarrow X$. Otherwise there is an almost-split sequence,*

$$0 \rightarrow \tau X \rightarrow F \rightarrow X \rightarrow 0.$$

- (iii) *If X is injective then its source map is $X \rightarrow X/\text{soc}(X)$. Otherwise there is an almost-split sequence,*

$$0 \rightarrow X \rightarrow E \rightarrow \tau^{-1}X \rightarrow 0.$$

- (iv) *For any indecomposable module U , the number of irreducible maps $U \rightarrow X$ is the multiplicity of U as a summand of F , where $F \rightarrow X$ is the sink map for X .*
- (v) *For any indecomposable module V , the number of irreducible maps $X \rightarrow V$ is the multiplicity of V as a summand of E , where $X \rightarrow E$ is the source map for X .*

Proof. (i) Corollary ??.

(ii) & (iii) Corollary ?? and Theorem taubijectionthm.

(iv) & (v) Theorem ??.

□

These results give us the following informal method for computing the Auslander-Reiten quiver of a path algebra kQ : Let X be an indecomposable module.

1. Find all the indecomposable projectives P_i of kQ .
2. Find $\text{rad}(P_i)$ for each of P_i .
3. Then we can draw a vertex P_i if we have already drawn the vertex $\text{rad}(P_i)$. Note that we start with the simple P_i .
4. Now only draw a vertex X if we have already drawn all vertices with an irreducible map to X .
5. If we have drawn a module X and we have drawn all irreducible maps coming out of it, we can draw $\tau^{-1}X$.
6. Keep going until we reach the indecomposable injective modules I_i of kQ .

We now end with some examples of Auslander-Reiten quivers:

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