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The Impact of Global Environmental Governance on Firm Innovation; Revisiting the Porter Hypothesis at the International Level.

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RESUME / ABSTRACT

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Bernhard Bieri
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Contents

List of Figures

List of Tables

Chapter 1

Introduction

Chapter 2

Litterature Review

The present paper draws from three distinct but complementary strands of the literature on environmental policy. First and foremost, we ought to characterize what is known in the literature as the *Porter Hypothesis* and distinguish the different versions that have been devised over the years. We will thus strive to understand the impact of increased environmental regulations on both innovative activity of firms and on overall firm performance before completing the analysis by highlighting works that looked at the impact of the nature of environmental policy on firm-level innovation. The next strand of the literature relates to the concept of *policy certainty* which highlights the importance of designing policies that Finally, and most central to our contribution, lies the literature on *International Environmental Governance* and the related methodological advances to understand it within a network framework.

2.1 The Porter Hypothesis

Over three decades ago, the Porter Hypothesis (PH) challenged the conventional Panglossian economic thinking that enhanced environmental regulation would lead to a decrease in economic performance of firms due to the increased constraints imposed on the firm (Porter 1991). The main intuition behind the Panglossian doxa is that if it were profitable for firms to follow a more sustainable production path, they would do so in the absence of regulations. On the basis of case studies, Porter however argues that well designed, market-based, pollution preventing policies would lead firms to create products that are more resource efficient and thus competitive on the international market. An example of the latter could be the implementation of more stringent fuel consumption standards for cars. Porter thus advances that this increase in environmental stringency, would force domestic automobile companies to make more fuel efficient cars which in turn would increase the competitiveness of domestic cars in the world market.

Porter and Von der Linde later formalize his initial criticism in Porter and van der Linde (1995) where they outline six main causal links between increased environmental regulations and innovation or firm performance. First, they contend that "regulation signals companies about likely resource inefficiencies and potential technological improvements. Second, they argue that"regulation focused on information gathering can achieve major benefits [in terms of environmental performance and economic performance] by raising corporate awareness". Third, they mention that "environmental regulation reduces the"uncertainty that investments to address the environment will be valuable". Fourth, they advance that outside pressure, which includes the regulatory framework firms have to comply with, is able to overcome organizational inertia and motivate innovation. The fifth reason put forward by the authors is that "regulation levels the transitional playing field" in the sense that regulation ensures that companies do not gain an unfair advantage until new and improved technologies are proven. The sixth and final argument pertains to an important nuance between the effect of regulation on innovation and competitiveness of firms in that compliance costs arising from environmental regulations might not always be offset by benefits brought by product innovations. Crucially, Porter and Van der Linde contend that most benefits occurring from increased innovation will arise in the medium to the long term due to the required time span for the innovation to bear fruits. Hence the existence of a lag between the implementation of an environmental regulation and a signal on innovation or economic performance metrics of firms is to be expected.

Due to its unorthodox nature, the Porter Hypothesis generated a strong debate among economists during the late 1990's and the early 2000's (Jaffe, Peterson, et al. 1995). Ambec, Cohen, et al. (2013) provide a clear overview of the various arguments proponents used to defend the *PH*. They define a first set of studies which underlines the fact that firms are driven by individuals who might not satisfy the assumptions of rationality required for firms to be deemed profit-maximizers. Indeed, managerial risk-aversion, resistance to change (Aghion et al. 1997), and a combination of lacking information and the cognitive capabilities to process the latter (Gabel and Sinclair-Desgagné 2001) may cause a mismatch between the utility maximizing behaviors of the management and the firm as a whole. Akin to this principal agent issue, Ambec and Barla (2002) argue that managers may exhibit rent-seeking behavior by retaining private information on the true costs of technological innovations that would improve productivity and the environmental performance of the firm. This essentially follows the organizational inertia and learning effects put forward by Porter and van der Linde (1995) and outlined above.

A second strand of the theoretical literature explore the role of market failures beyond the pure environmental externalities generated by pollution and how increased environmental regulations could overcome them. Examples of this strand include situations where firms are first movers within international markets characterized by imperfect competition where domestic production may increase as a result of more stringent environmental regulation (Simpson and Bradford 1996). Another common market failure that could lead to the coexistence of the *PH* alongside profit-maximizing firms are information asymmetries between households and firms. The main idea here is that by setting industry standards or labels, firms are able to credibly communicate the environmental benefits of their products and overcome the asymmetry (Ambec and Barla 2007). Finally, the non-exclusive nature of R&D may lead to spillovers from the innovating firm to other firms in the industry. This may lead the economy to be in a bad equilibrium where firms invest too little in environmental technologies. If this is indeed the case, then regulations can level the playing field among firms and lead to a move to the higher, more R&D intensive equilibrium (Mohr 2002).

On the empirical front, much has been written to reinforce the initially very theoretical debate surrounding the Porter Hypothesis. To facilitate its analysis, Jaffe and Palmer (1997) divided the original hypothesis into three distinct ones. What is known as the “Strong Porter Hypothesis” (*SPH*) links environmental regulation to firm competitiveness. The “Weak Porter Hypothesis” (*WPH*) links regulation to innovation, and the “Narrow Porter Hypothesis” argues that flexible market-based regulations are more effective in generating innovation than stricter command-and-control policies[1].

The empirical literature analyzing the weak version of the Porter Hypothesis usually operationalizes innovation as R&D expenditures or through (aggregate or sector specific) patent counts. When instead analysing the strong version of the *PH* studies usually rely on firm profits. On the right hand side, the independent variable, environmental policy stringency, was initially proxied

[1]Since we will focus on the former two two hypotheses, we will not elaborate on the “narrow” hypothesis in this literature review.

by pollution abatement costs (Jaffe and Palmer 1997) or energy prices (Newell et al. 1999) before being more holistically estimated via the use of indicators such as the Environmental Policy Stringency (*EPS*) indicator developed by the OECD (Kruse et al. 2022) or national firm-level surveys such as the Community Innovation Survey[2] (Eurostat 2022). As we will outline more in detail in section 3 of the paper, we will take the modern approach and use the EPS index to proxy for environmental regulation stringency at the domestic level and patent counts and business R&D expenditures to proxy inventive activity of firms. The weak version of the Porter Hypothesis is found to be the most consistently verified hypothesis among the three as outlined in the meta-analysis by Cohen and Tubb (2018). The authors of the meta-analysis namely highlight the following points:

- Early studies tend to find a negative relationship between environmental stringency and innovation/competitiveness. More recent studies find a positive relationship between the two variables.
- Cross-country studies are more likely to find a positive link than firm-level studies. One possible reason for this can be found in the fact that innovative activity of upstream equipment manufacturers or new entrants may also respond to changes in the regulatory frameworks within an industry (Noailly and Smeets 2015; Sanyal and Ghosh 2013)[3].
- Studies incorporating a temporal lag between the change in regulation stringency and inventive or profitability outcomes are more likely to find a positive relationship. This echoes once again the original formulation of the Porter Hypothesis which states that while regulation may hurt short term competitiveness and productivity, the long term effects would be positive.

These findings will guide us in the elaboration of a panel model that will be outlined in more detail in section 3. Let us now turn our attention to the second strand of literature use to guide our empirical strategy and examine the impact of policy (un-)certainty on innovation.

[2]See Cohen and Tubb (2018) for a recent meta-analysis of the Porter Hypothesis and an outline of the different measures used.

[3]Furthermore, Cohen and Tubb (2018) note that "[t]o the extent that the Porter Hypothesis as originally formulated focused on the competitiveness of nations, this finding is of particular interest [...]". In other words, since the original *PH* focused on nations as the unit of analysis, it is natural to take this unit of analysis when empirically testing it.

2.2 The Role of Policy Certainty on the Innovative Behavior of Firms

While the empirical literature on the impact of policy certainty on innovation is more recent and less abundant than the one on the Porter Hypothesis, a number of papers have investigated it. The literature of the impact of policy certainty on innovative activity was derived from the one that links policy uncertainty and investments in tangible assets. Early theoretical contributions outline that non-reversible investments are often delayed or scrapped if firms experience regulatory uncertainty via an increase in the utility derived from the status-quo[4]. On the empirical front, Alesina and Perotti (1996) were the first to investigate this link with a cross-section analysis of over 70 countries. More specifically, they find that more unequal countries are more likely to be politically unstable and political instability in itself has an adverse effect on investments in tangible assets. Additional empirical evidence highlighting the negative effect of policy uncertainty was provided by Bloom, Bond, et al. (2007) who extend the analysis to a panel model, Julio and Yook (2012) who highlight a negative impact of being in an election year on firm investments, and Gulen and Ion (2016) who leverage the Economic Policy Uncertainty index developed by Baker et al. (2016) to describe a similar effect within a panel analysis.

This negative effect between policy uncertainty and tangible asset investments need not hold for intangible investments in R&D since the latter are different and are namely characterized by a long-term horizon and a fat tailed risk distribution[5]. Nevertheless, a growing game theoretical literature argues that short-term agreements are less conducive to investments in green R&D than long-term agreements due to the comparatively higher hold-up phenomenon when renegotiations are frequent (Harstad 2016). This phenomenon is mainly explained by the fact that countries that are more efficient in mitigating or abating emissions due to previous investments in the related technology will be asked to leverage their competitive advantage and bear the brunt of the emission reduction in negotiations. Bhattacharya et al. (2017) were the first to investigate the effect of policy uncertainty on innovation outcomes (i.e. patent quantities and citations) empirically. They extend the theoretical model proposed by Edmans (2009) on managerial myopia by adding economic uncertainty, a measure of policy state and a measure of policy uncertainty. Using this

[4] See Bernanke (1983) and Bloom, Draca, et al. (2016) for respectively a seminal and a recent theoretical model.

[5] This characteristic is a product of the trial and error nature of the R&D process where only a small subset of research endeavors are successful and profitable.

theoretical framework, they test whether the pure effect of country level policy orientation, as proxied by the Database of Political Institutions, and policy uncertainty, as proxied by the occurrence of election events, have an impact on firm-level innovation (Keefer 2012). Crucially, they are able to show that innovation is more affected by policy uncertainty than by policy itself. This leads to the conclusion that a politically stable environment is beneficial to R&D investments and confirms the findings of the game theoretical literature (Beccherle and Tirole 2011; Harstad 2016).

These studies are looking at the aggregate level effect between policy certainty and innovation. More recently however, newspaper indices on both climate policy uncertainty (**gavriilidisMeasuringClimatePolicy2** and on climate policy salience became available (**noaillyHeardNewsEnvironmental2021**). These indexes are both built by programmatically analyzing US newspaper articles over a given period to detect the co-occurrence of a given set of words[6]. **gavriilidisMeasuringClimatePolicy2021** used his index to show that increased policy uncertainty lead to a reduction of CO2 emissions. He further argues that, this might be due to either a decrease in energy consumption and a reduction in non-essential transport or an increase in the demand for renewable energy consumption and an associated increase in climate-friendly innovations. On the other `hand@noailly2021heard` were able to leverage their policy salience index to demonstrate a positive link between policy salience and the probability of cleantech startups receiving venture capital funding. While these indices are able to inform research on the link between environmental policy uncertainty/salience and innovative inputs and outcomes for the US, they cannot yet be used within a panel framework. Furthermore, these indices are symptomatic in that they capture perceptions of an aggregate policy environment. As both papers outline the aggregate sentiment as proxied by newspaper articles, they do not consider the root causes of this uncertainty or salience.

This underlines the importance of considering the potential variables which influence domestic environmental policy certainty and may reinforce innovative activity. This leads us to hypothesis that international commitments, in the form of the the participation in international environmental agreements, may reinforce the credibility of domestic environmental policy and thus increase the effect of environmental policy stringency on innovation. We will refer to this effect as the

[6] Both follow the methodology outlined in the Economic Policy Uncertainty index developed by Baker et al. (2016) and apply different keywords to the programmatic analysis of US newspapers.

indirect effect of international environmental governance on environmental innovation. The complementary *direct effects* of international environmental policy have been outlined in comparative studies within the international relations and political science literatures and will analyzed in more detail in the next subsection.

2.3 Assessing the Formation and the Effectiveness of International Environmental Governance

While the literature on global environmental governance does not specifically address the link between the participation rate of a country in the international governance complex and the rate of innovation of its firms, it offers insights in two main ways. First, an important strand investigates the drivers motivating countries in participating in international environmental treaties. A second complementary strand

explores the effect of international proximity and cooperation on environmental performance. We will analyse each strand in turn and focus on deriving the *direct effects* between the embeddedness of a country in the international environmental governance network and the innovation process to motivate our theoretical approach presented in the next chapter. The first strand of this literature leverages game theoretical or social network analysis methodologies to understand the formation of cooperative ties in the environmental governance network. The latter methodologies are of a particular relevance in our case since they acknowledge the interdependence of the cooperative tie formation process.

The initial methodological lens through which international environmental cooperation has been assessed is game theory. The main unit of analysis in early papers was often a single agreement such as the Montreal Protocol (Barrett 1994). More recent theoretical advances in the literature consider the participation in IEAs as a static or a dynamic game with repeated interactions between countries [beccherleRegionalInitiativesCost2011; harstadDynamicsClimateAgreements2016; Battaglini and Harstad (2016)].[7] The main conclusion of this strand that is of a particular interest to us is that long term agreements create a more certain policy environment and help reduce the uncertainty that surrounds investment in green R&D. However, although dynamic in nature, the aim of these models is to devise the characteristics of an effective prototypical

[7]The majority of the empirical evidence within the game theoretic literature comes from experimental economics. See e.g. Tavoni et al. (2011) and Barrett and Dannenberg (2012)

international environmental agreement. In other words, it does not consider the emergence of a *international environmental governance network*. This underlines the necessity of adopting a polycentric approach in the analysis of the *network* of environmental governance where agents interact at different levels (Ostrom 2009; Jordan et al. 2018) in a dynamic context. Social network analysis methods have thus been employed to understand the drivers of international cooperation within such a framework. The main benefits of using such an approach to analyse the emergence of cooperative ties is that these depend on both the *characteristics* of the agents that form them and the *structure* of the network they exist in. **kinneNetworkDynamicsEvolution2013** underlined that states are more likely to form bilateral cooperation ties if they share agreements with third parties[8].], if they sign more agreements overall, and if they exhibit similar characteristics with their bilateral partners. While Kinne examines a unimodal network of bilateral agreements between the end of the Second World War and 1980 due to data availability, Hollway and Koskinen (2016) further his analysis by examining the bipartite structure of network and highlight the importance of multilateral agreements in the process of triadic closure. While this first strand of the literature on the formation of environmental cooperation does not have a direct impact on the rates of innovation of countries, it is useful to understand the relevance of social network analysis as a mean to study the concurrent effects of the position of an agent in a network and their characteristics as opposed to the previously discussed game theoretical approach. Moving forward, we will therefore see the environmental governance complex as a network and highlight the effects of the topological attributes of countries on innovative inputs and outcomes.

The second strand of the literature on environmental governance grew from the fact that domestic policy is affected by *both* domestic and international factors (Drezner 2008; Hays 2009; Jahn 2016). As such, it investigates the *effects* of international environmental cooperation on country level variables such as environmental performance and innovation. This specific strand is surprisingly understudied and most evidence presented below either theoretical or qualitative. To our knowledge, the only attempt to investigate the link between the intensity of participation in the environmental governance complex quantitatively was provided by Jahn (2016) and is discussed below, after underlining a number of qualitative stylized facts on environmental cooperation.

[8]This confirms the triadic closure phenomenon highlighted by Granovetter Granovetter (1973)

The Stern review provides initial theoretical and qualitative insights into the ways increased international cooperation may facilitate eco-innovation (Stern et al. (2007), chapters 16 & 24). The main lens the review considers the link between international cooperation is one of portfolio management where cooperation is motivated by knowledge sharing[9], efficiency gains through the coordination of R&D portfolios and finally the pooling of risks which are a characteristic of the innovation process. In addition to this portfolio approach, they underline the importance of setting of international environmental standards which may reinforce domestic environmental regulation (Stern et al. (2007), chapter 24.6). In other words, Stern argues that international co-ordination on performance standards leads to larger markets being affected than if countries were to act in isolation which may lead the market to tip from one equilibirium to another due to a combination of network feedback effects, economies of scale or technological lock-in effects (See Barrett and Stavins (2003) for a discussion). These qualitative insights on R&D cooperation and international standard setting are not the only channels in which international environmental policy may affect innovation and environmental performance as we have outlined above in the previous subsection.

Jahn (2016) complements these insights with an analysis of the effect of supra-national factors such as the membership in international organizations, the membership in international treaties as well as more general effects such as globalization on multiple indices of environmental performance of OECD countries he constructed[10]. While Jahn's dependent variable is environmental performance, his central argument on the relevance of the *combination* of both national an international policy factors is nevertheless valuable in the context of this study as it highlights the rise of international environmental policymaking. The rising importance of international environmental cooperation has further been highlighted by Carattini et al. (2021) who illustrate it by using a network analysis approach to analyse the ECOLEX dataset(UNEP, IUCN, FAO 2022). The aim of their paper is to derive a set of stylized facts on the intertemporal evolution of the network of international agreements by constructing a "cooperation network" between states.[11] After constructing this cooperation network, Carattini et. al describe the evolution of the position

[9] To namely overcome the developed/developing divide and ensure a fair transition for developing countries where climate targets are met but not at the expense of the growth of developing countries.

[10] Other comparative analyses complement his findings: see e.g. Holzinger et al. (2008) and Bauer and Knill (2014).

[11] Section 3 provides the reader with more detail about the construction of such a cooperation network and in particular the theoretical implications associated with such a measure.

of states within this network. They narrow down their observations to the following four stylized facts:

1. "Meaningful environmental cooperation emerged in the late 1970's."
2. "Environmental cooperation has become closer, denser and more cohesive."
3. "The environmental cooperation network, while global has a noticeable European imprint."
4. International environmental cooperation started with fisheries agreements but the contemporary focus has shifted towards the management of waste and hazardous substances.

These stylized facts empirically confirm observations from the theoretical literature on international environmental agreements that highlight their growing importance (Jordan et al. 2018; Ostrom 2009).

In conjunction with the literature on policy certainty shown in the previous section, the increased importance of international environmental politics leads us to draw a model that investigates the concurrent effects of national and international environmental policies on the innovative behavior of firms. The aim of our paper is therefore to investigate whether or not the relative position[12] of a country in the global environmental governance network affects the different versions of the Porter Hypothesis. Now that the theoretical motivation of our study is set, let us outline our empirical strategy in the methodology section.

[12]In a topological sense.

Chapter 3

Methodology and Data

This section will outline the computation of a novel set of centrality measures which will be used in the subsequent analysis to proxy the relative importance of countries within the international environmental governance complex and account for the increasing importance of international policy to tackle environmental challenges. In what follows, we will describe the construction of the bipartite membership network of international agreements[1] and the extraction of a monopartite cooperation network which defines links between countries as the number of agreements that have been signed in common. We then statistically validate this projection by comparing the resulting observed one cooperation network with a null model. This process is also commonly known as *backbone extraction*. Finally, we describe the computation of two centrality indices that will proxy the intensity and the certainty of international policy. Finally, we will define the empirical panel model that we will estimate in the next section.

3.1 Defining Hypotheses:

3.2 Constructing international environmental cooperation centrality measures:

We leverage the ECOLEX dataset to construct country level measures of embeddedness in the international environmental cooperation network (UNEP, IUCN, FAO 2022)[2]. This dataset lists environmental agreements between two or more parties and the related membership actions over

[1]Note that we interchangeably use bimodal and bipartite as adjectives to qualify the nature of the original membership network. The original network is both bimodal, since it has two different types of agreements, and bipartite since it does not have links between two nodes of the same type. (Borgatti 2009)

[2]To be more specific, we use a pre-scraped version included in the `{manyenviron}` package (Hollway 2021) which was originally used in Sommer (2020)

the period between 1868 and 2018 and contains over 25000 individual membership actions.[3] We follow Carattini et al. (2021) and retain agreements that were signed in the Post-war period starting in 1948. We retain 21270 individual membership actions after filtering out agreements signed before 1948. After further cleaning the data by excluding observations on which we do not have identifying information such as the date of the ratification of the agreement and the date of entry into force or the country which is the subject of the membership action, we retain 18878 individual membership actions that describe 521 individual international environmental agreements.

[3]See Table 3.1 describing the structure of the dataset and displaying the first few observations.

Table 3.1: ECOLEX Dataset Head

ecolexID	treatyID	CountryID	Title	Beg	End	SignatureCountry	Rat	Force	DocType	GeogArea	Subject
TRE-001148	CBD_1992A	GIN	Convention On Biological Diversity	1992-06-12	NA	1992-06-12	1993-05-07	1993-12-29	M	G	Wild species & ecosystems
TRE-000557	CFAOUN_1948A	FJI	Constitution Of The Food And Agriculture Organization Of The United Nations	1948-01-01	NA	NA	NA	1948-01-01	M	G	Legal questions
TRE-000498	INTRMO_1948A	ARG	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1966-10-05	1966-10-05	M	G	Sea
TRE-000498	INTRMO_1948A	AUS	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1952-02-13	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	BEL	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1951-08-09	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	CHE	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1967-01-13	1967-01-13	M	G	Sea
TRE-000498	INTRMO_1948A	CHL	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1972-02-17	1972-02-17	M	G	Sea
TRE-000498	INTRMO_1948A	COL	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1974-11-19	1974-11-19	M	G	Sea
TRE-000498	INTRMO_1948A	ERI	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1958-03-17	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	FJI	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1959-04-21	1959-04-21	M	G	Sea
TRE-000498	INTRMO_1948A	GAB	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1952-04-09	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	GEO	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1949-02-14	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	GRD	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1958-12-31	1958-12-31	M	G	Sea
TRE-000498	INTRMO_1948A	IRL	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1959-01-06	1959-01-06	M	G	Sea
TRE-000498	INTRMO_1948A	IRN	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1951-02-26	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	JAM	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1957-01-28	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	LBR	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1966-05-03	1966-05-03	M	G	Sea
TRE-000498	INTRMO_1948A	NOR	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1949-03-31	1958-03-17	M	G	Sea
TRE-000498	INTRMO_1948A	PRT	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1960-03-16	1960-03-16	M	G	Sea
TRE-000498	INTRMO_1948A	PRY	Convention On The International Maritime Organization	1948-03-06	NA	1948-03-06	1976-03-17	1976-03-17	M	G	Sea

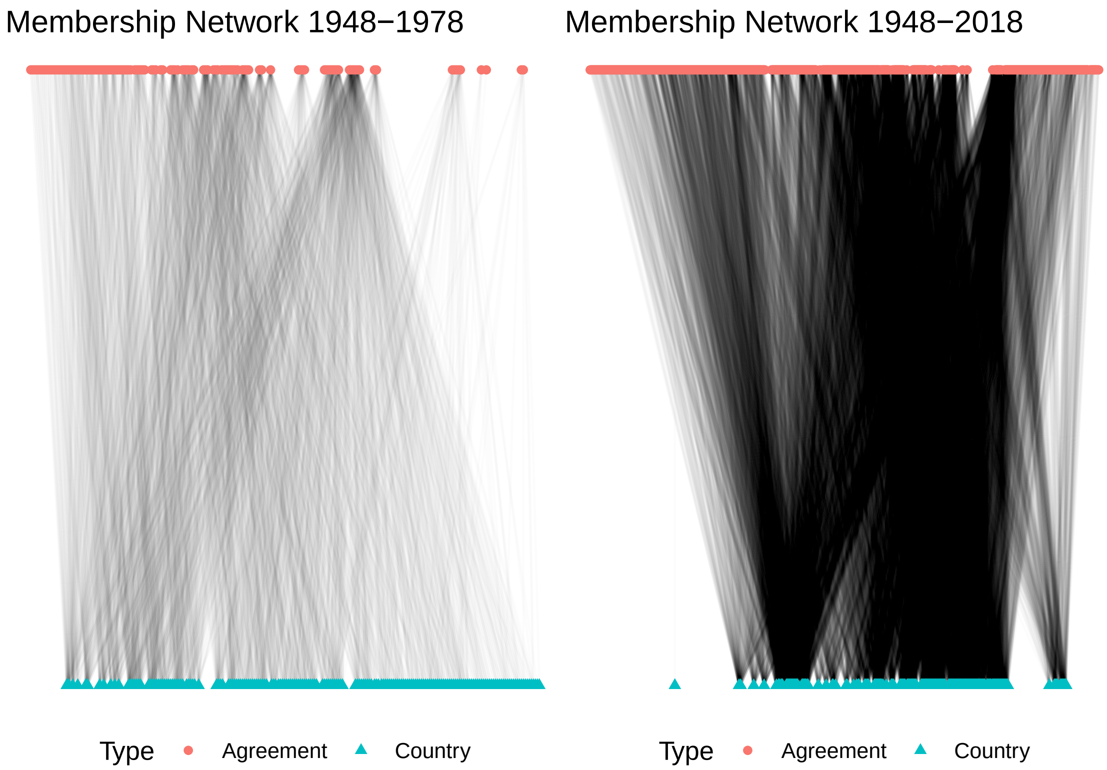
3.2.1 From a Bipartite Membership Network:

The ECOLEX dataset presented above in 3.1 can be visualized as an annual series of undirected, unweighted, bipartite/bimodal networks. This can be done in the form of a yearly incidence matrix $I^t_{C\times A}$ where each row corresponds to a country (an agent) and each column to a treaty (an artifact) (Latapy et al. 2008). The main theoretical difference between the two sets of nodes is that the former has agency over the links while the latter does not.[4] i^t_{ik} equals 1 if country i has ratified agreement k which entered into force during or before year t and 0 otherwise. A country can only be a member of a treaty once which implies that $i^t_{ik} \in \{0,1\}$.

$$I^t_{ik} = \left.\overbrace{\begin{pmatrix} i_{1,1} & i_{1,2} & i_{1,3} & \cdots & i_{1,A} \\ i_{2,1} & i_{2,2} & i_{2,3} & \cdots & i_{2,A} \\ i_{3,1} & i_{3,2} & i_{3,3} & \cdots & i_{3,A} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ i_{C,1} & i_{C,2} & i_{C,3} & \cdots & i_{C,A} \end{pmatrix}}^{\text{Agreements}}\right\}\text{Countries}$$

We can also visualize the bipartite/bimodal membership network directly and distinguish agreements from countries. The network is depicted in @ref(fig:ECOLEX_bipartite_network) represents the membership network with all agreements that entered into force respectively during the period of 1948 and 1978 and 1948 and 2018. This shows that the network grew denser as agreements were signed, ratified and entered into force over time. To explore the intertemporal evolution of the structure of the network, we will divide this network and construct yearly snapshots of the membership graph whose incidence matrix we define as $I^t_{C\times A}$ which is one of the two standard methods used in social network analysis to account for the intertemporal evolution of a network (Everett and Borgatti 2013).

[4] This distinction will inform the choice of the backbone extraction algorithm as outlined below.



3.2.2 To a Monopartite Cooperation Network:

While we could further analyze this network directly, we will transform it into a more easily interpretable one mode network by using a projection and retaining only significant edges through a backbone extraction algorithm. We will thus broadly follow Carattini et al. (2021) while ensuring that our results are not contingent on the backbone extraction algorithm since the theoretical underpinnings of the latter are still somewhat unclear in empirical social network analysis (Neal et al. 2021).

We begin by creating a naive projection of the membership network. To perform this naive projection we multiply the yearly incidence matrix $I^t_{c \times a}$ defined above by its transposed $I^t_{A \times C}$ as follows:

$$I^t_{C \times A} I^t_{A \times C} = Adj^t_{C \times C}$$

Where $Adj^t_{c \times c}$ is the adjacency matrix of the projected cooperation network in which Adj^t_{ij} is the number of observed co-signed agreements between the two countries that entered into force in the interval $[1948; t]$. These weights capture the intensity of the environmental cooperation between two countries much like Newman (2001) captured collaboration within a bipartite network of scientific collaboration. Concurrently, it implies that bilateral treaties, ceteris paribus, carry a greater weight in the cooperation network than multilateral treaties. This is consistent with the heterogeneous role both play within the environmental governance network. As highlighted by Hollway and Koskinen (2016), bilateral treaties are akin to contracts between two parties while multilateral treaties serve "normative [...] law-making tools". While both types may act as policy stringency signals, bilateral treaties carry more weight through their specific contractual nature hence developing a greater policy stringency signal for firms.

We cannot, however, directly analyze this cooperation network as the resulting *naive* monopartite network, depicted in the first panel of @ref(fig:ECOLEX_monopartite), still suffers from two issues. First, nodes with larger degrees in the original bipartite membership network (e.g. agreements with a larger number signatories or countries having signed a larger number of agreements) will bear stronger edges in the projected network. In other words, if *country A* and *country B* are bound by the same 5 agreements and have each signed 5 agreements in total, they are conceptually "closer" than *country C* and *country D* who share the membership in 10 agreements but have each signed a total of 50 agreements (Borgatti and Halgin 2011; Latapy et al. 2008; Neal 2014; Saracco, Straka, et al. 2017). However in the resulting one-mode projection, the latter will be weighted more than the former. The second issue relates to the fact that *naive* projections may lead to the emergence of spurious cliques in the projection that are due to a node with a single connection to the opposite layer in the original bipartite network (Saracco, Straka, et al. 2017). To solve these two common issues, we leverage what is known as a backbone extraction algorithm to retain only the statistically significant edges from the naive projection e.g. the edges that appear more frequently in the projection than expected by a given null model.

3.2.3 Correcting the Monopartite Cooperation Network:

We will use the following three distinct backbone extraction methods to ensure that our results are not the product of the choice of a particular extraction method alone. This is especially crucial since we do not have a "ground truth" or a counterfactual monoparite cooperation network to compare the corrected projection to. All three considered algorithms follow the same process in that they impose a constraint M on the original bipartite network and reshuffle the values of the incidence matrix $I_{C \times A}$.[5] In other words, we consider the set of all possible permutations of the original incidence matrix $I^t_{c \times a}$ containing the same countries and treaties and satisfying the constraint M. We call this set $\mathcal{I}^M$ which is consists of the individual permutated matrices I^*. The algorithm then constructs the one-mode projection of I^* as follows: $P^* = I^* \times [I^*]^T$ Recall that when performing the naive projection, we defined p_{ij} as the observed number of co-signed treaties between country i and country j. To decide whether an edge between i and j should be included in the backbone of the projected network, the algorithm compares the observed value p^t_{ij} to the simulated one in P^* which we call p^*_{ij}. We therefore define the following two-sided hypothesis test to characterize the presence (or absence) of a tie p^B_{ij} in the backbone P^B based on a significance level α.

$$p^B_{ij} = \begin{cases} 1 & \text{if } \Pr\left(p^*_{ij} \geq p_{ij}\right) < \frac{\alpha}{2} \\ 0 & \text{else} \end{cases}$$

As described in Neal et al. (2021), we use a two-tailed test since we would like to filter out both uncommonly small *and* uncommonly large collaborative ties in the projection. Neal (2022) point out that since we perform this hypothesis test for every non-null edge, we will inflate the Type-I error i.e. include too many false positives in our corrected graph. [6] Following therefore leverage the False Discovery Rate multiple test correction method which sorts the observed p-values in an increasing order before retaining all edges with a p-value satisfying P-value$_d \leq \frac{d}{m}\alpha$ where $d \in \{1, \ldots, e\}$.

CITE BENIAMINI HOCHBERG 1995

Finally, this hypothesis test yields a binary correction matrix which informs us whether to keep a tie in the naive projection or not and thereby solves both issues of the naive projection described above. Now that we have a general understanding of the process of a backbone extraction algorithm, we turn to the following three subsections which will focus on the differences between the different algorithms that lie in the nature of the constraint they impose on the simulated networks. We will thus consider in turn the Fixed Row Model, the Fixed Degree Sequence Model, and the Stochastic Degree Sequence Model.

[5] We broadly follow the notation used in Neal et al. (2021) where each backbone extraction method is described in more detail. Furthermore, we abstract from superscript t to indicate the time period of the network as we apply the backbone extraction method to each temporal snapshot of the network.

[6] The significance level α defines the probability that a given edge is included in the backbone. Since we run this test over e edges, the probability that we detect at least one such false positive across our test equals $1 - (1 - \alpha)^e$ which is strictly increasing in the number of tests e.

Fixed Degree Sequence Model:

The Fixed Degree Sequence Model (FDSM) is a microcanonical backbone extraction method in that the constraint that it imposes on the set of possible permutations $\mathcal{I}^{FDSM}$ is satisfied *exactly.*[7] More specifically, the FDSM algorithm sets the degrees of each agent and each artifact to be equal to the degree sequences of the observed network. In our context, it implies that the row and column sums of the simulated I^*_{ik} are to be equal to those of the observed network I_{ik} under the FDSM algorithm.

$$I^*_{ik} = \begin{array}{cl} \begin{pmatrix} 1 & 1 & 1 & \dots & 1 \\ 0 & 1 & 0 & \dots & 1 \\ 0 & 0 & 1 & \dots & 1 \\ 0 & 1 & 0 & \dots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & 0 & \dots & 1 \end{pmatrix} & \begin{array}{l} \sum_{k=1}^{A} i_{1k} \\ \sum_{k=1}^{A} i_{2k} \\ \sum_{k=1}^{A} i_{3k} \\ \sum_{k=1}^{A} i_{4k} \\ \vdots \\ \sum_{k=1}^{A} i_{Ck} \end{array} \\ \begin{array}{ccccc} \sum_{i=1}^{C} i_{i1} & \sum_{i=1}^{C} i_{i2} & \sum_{i=1}^{C} i_{i3} & \dots & \sum_{i=1}^{C} i_{iA} \end{array} & \end{array}$$

As Neal et al. (2021) point out, the main advantage of this method is that it is able to alleviate the two issues plaguing our *naive projection* outlined above by controlling for the vector of degrees. Intuitively, we retain the cooperative edges that occur more often than expected by the null model in the observed projection.[8] The main disadvantage of such an algorithm is that it is ill suited for large bipartite networks due the computational complexity of the algorithm (Neal et al. 2021). A set of alternative models has been developed to alleviate this computational issue, among which are the Fixed Row Model and the Stochastic Degree Sequence Model which we define below.

Fixed Row Model:

Like the FDSM, the Fixed Row Model (FRM) is also a microcanonical algorithm. However, the main difference is that it imposes the degree sequence constraint on the row sums of the incidence matrix only.[9] [10] That is, the degree of every *agent*/country is strictly controlled for, which implies that in all simulated networks, a country will be bound by the same number of

[7] This stands in opposition to canonical extraction algorithm that impose the constraint only *on average*.

[8] Vasques Filho and O'Neale (2020), degree sequences of the bipartite network are chiefly responsive for the structure of its monopartite projection.

[9] E.g.

$$\forall_{i \in \{1,\dots,C\}} \sum_{k=1}^{A} i_{ik} = \forall_{i \in \{1,\dots,C\}} \sum_{k=1}^{A} i^*_{ik}$$

[10] The FRM model is also sometimes referred to as the hypergeometric model (Tumminello et al. 2011).

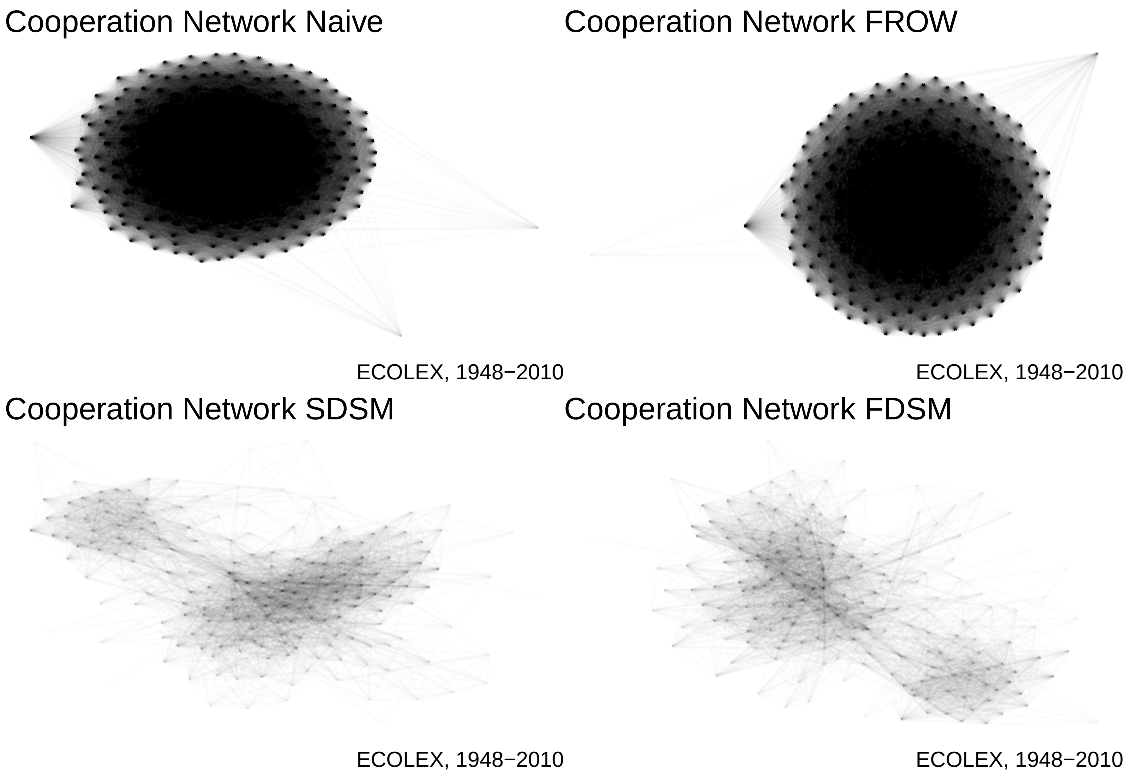
agreements than in the observed network. However, an agreement is free to have a different number of total signatories. This leads us to the reason why we are not considering the Fixed Column Model: agency. Recall that we previously defined two distinct sets of nodes depending on whether or not the nodes posses agency over the links they would like to create or dissolve. Since agreements do not have agency and are constructed through the will of countries, we constrain the latter's degree only. Carattini et al. (2021) applied the Bipartite Partial Configuration Model which is the canonical version of the FRM algorithm, to their membership network (Saracco, Straka, et al. 2017). This implies that the restriction imposed on the degree sequence of countries is only satisfied *on average* over all simulations. Since our membership network is small enough to be corrected by applying the more computationally intensive FRM algorithm, we follow the latter as it carries more information about the structure of the original bipartite network than the BiPCM algorithm (Saracco, Straka, et al. 2017).

Stochastic Degree Sequence Model:

The Stochastic Degree Sequence Model (SDSM) is a canonical algorithm that imposes a constraint on both the degree sequence of countries and on the degree sequence of agreements like the FDSM extraction method. However, the set of simulated networks satisfy this constraint only *on average*. In our case, this implies that the average number of member countries in a given international agreement k in the set of simulated networks is equal to the number of countries in the observed membership network. Conversely, it also implies that the average number of agreements signed by a given country i in the set of simulated networks is equal to the average number of agreements signed by country i in the observed network. Several methods exist to simulate networks satisfying this constraint which are compared in terms of accuracy and computational speed in Neal et al. (2021). The authors show that the Bipartite Configuration Model (BICM) is both the fastest and most accurate method to generate simulated network satisfying the average condition (Saracco, Straka, et al. 2017). We thus leverage it as our third and last backbone extraction model.

Comparing the Projections:

Before moving on to the definition of the various centrality measures we will use to measure the level of international embeddedness of countries within the network of international environmental agreements, we will compare the resulting corrected projections. We namely see that the correction of performed by the FROW backbone extraction process retains about 90 percent of the edges of the naive projection which leads to an overly dense network. We will therefore not consider it in the further analysis as it does not solve the two issues which we try to correct. This is consistent with Carattini et al. who mention that their BiPCM-corrected cooperation network's density is so high that almost every node is connected to each other (Carattini et al. 2021). On the other hand, both the SDSM and the FDSM retain on average about 15 percent of the most significant edges present in the naive projection. This ensures that we capture the true cooperative network and not a statistical artifact caused by the two issues we are trying to correct for. We will therefore compute the centrality scores on the basis of the latter two corrected networks.



3.2.4 Selecting and Computing Network Centrality Measures:

Now that we constructed and corrected the monopartite cooperation networks, we can characterize the topological position of a given country within the network and construct proxies for the *embeddedness* of a country in the international environmental governance complex. While there exist a multitude of centrality indices to characterize the position of a country and no unifying theoretical framework for defining it, we will consider the commonly used strength centrality measure and the eigenvector centrality measure which we will theoretically justify in turn.

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Strength Centrality:

The strength of a node in an undirected and unweighted network measures the number of ties emanating from a node and weights them by their respective weights as follows:

$$s_i = \sum_{j=1}^{N} a_{ij} w_{ij}$$

Strength centrality echoes the proxy Jahn (2016) used to measure embeddedness in the international governance complex in that it captures the sum of cooperative ties of a given country within the weighted network of ties. Hence we expect that a country with a higher level of strength, ceteris paribus, will be more embedded in the international environmental agreement network. As stated in the previous chapter, we expect that this increased embeddedness leads to an increase in environmental innovation through both direct effects of the international policy framework and the indirect effects of a greater policy certainty. While we cannot distinguish both channels in this study, we expect that the node strength captures a relatively greater share of the direct effects of the increased embeddedness on innovation as it measures the quantity of agreement a country is bound by. The opposite can be said of the eigenvector centrality measure we define below.

Weighted Clustering Coefficient:

The weighted clustering coefficient extends the notion of embeddedness by examining the centrality of a node. In mathematical terms, the eigenvector centrality of a node in a weighted and undirected network is defined as the following index:

$$c_i^w = \frac{1}{s_i\,(k_i - 1)} \sum_{j,h} \frac{(w_{ij} + w_{ih})}{2} a_{ij} a_{ih} a_{jh}$$

In our international cooperation network, this can be trans

3.3 The Empirical Model:

We define a panel model and consider all OECD countries (as of 2021) over the time period between 1990 and 2015.

$$y_{it} = \beta_1 \text{EPS}_{it} + \beta_2 \text{Strength}_{it} + \beta_3 \text{WeightedClustering}_{it} + \beta_4 X_{it} + \alpha_i + \delta_t + u_{it}$$

3.4 Descriptive Statistics:

Some plots

Chapter 4

Results

4.1 An intro to R chunks

One of the most useful parts of *RMarkdown* is the ability to weave or 'knit' text (as we've seen in the previous three chapters) together with the code that produces tables and graphics for your final document. This has various advantages such as:

- *coherence*: for you, having your analysis and text together means keeping a coherent story together about why you did the analysis you did, how you got to your results, and what your interpretation of these results is
- *amendability*: this gives you an opportunity to update the code, for example by filtering the data in a different way, and rerun the code to see how any statistics, tables or graphs related to the data may have changed
- *reproducibility*: this also, importantly, supports a reproducible workflow such that you, or others, can rerun and test the code at a later point

To 'knit' such text and code together, code for particular graphs or tables should first be inserted into the text in 'chunks'. These chunks are opened with three backticks and closed in a new line with another three backticks. The code that produces the desired output is included between these lines, which can include comments etc. A key part of these chunks are the chunk parameters, which are included in braces immediately following the first set of backticks. The first parameter indicates the programming language. The second parameter, which is optional and should be separated from the first parameter only by a space, is a chunk label. It is important that this chunk label includes no spaces and is unique to this chunk. Then, separated by commas, are any additional parameters included. In the figure below, two examples are included: whether or not the code itself should be shown (`echo`) and whether or not the code should be evaluated or run (`eval`). Other parameters that we will see later include figure width, captions, etc.[1]

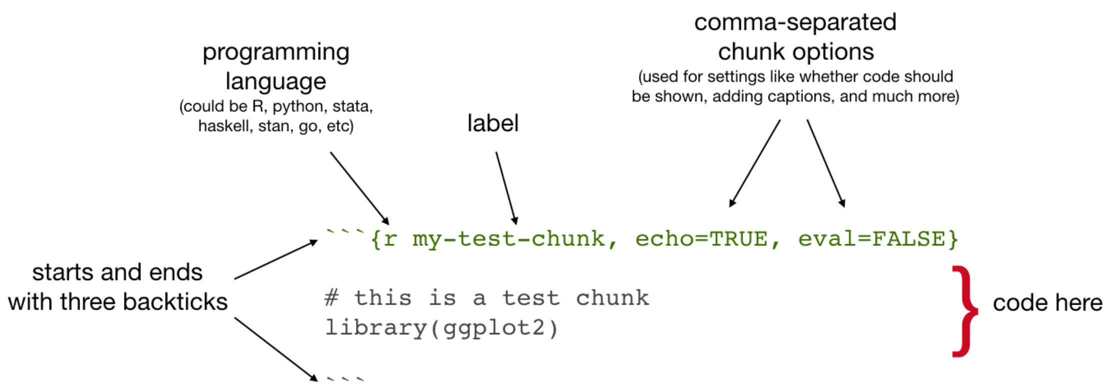


Figure 4.1: Chunk parts

In the code chunk shown in Figure 4.1, we can see that it is loading a package library. Functions and objects loaded or created in earlier chunks are cached by default and thus held on to for use in later chunks. It is therefore quite common to have a chunk early on in your chapter (or even your whole dissertation) that loads a number of the packages you need later on. As an example, below is a short code chunk that loads a set of **R** packages that we are going to rely on for the rest of this chapter.

When you click the **Knit** button above in RStudio a document will be generated that includes both content as well as the output of any embedded **R** code chunks within the document. If you need a graphic or tabular material to be part of the text, you can just put it inline. If you need it to appear in the list of figures or tables, it should be placed in a code chunk.

In the remainder of this chapter, we will see how to use code chunks to include figures, load and summarise data, and present results from your analysis.

4.2 Including external figures

First, we will treat how to include figures in *RMarkdown* in more detail. If your thesis has a lot of figures, *RMarkdown* might behave better for you than your usual word processor, which can have a tendency to . One perk is that it will automatically number the figures accordingly in each

[1] More information is available at `https://yihui.org/knitr/options/`.

chapter. You'll also be able to create a label for each figure, add a caption, and then reference the figure in a way similar to what we saw with tables earlier. If you label your figures, you can move the figures around and *RMarkdown* will automatically adjust the numbering for you. No need for you to remember! So that you don't have to get too far into LaTeX to do this, a couple **R** functions have been created for you to assist. You'll see their use below.

4.2.1 Numbering and labelling figures

You don't need to number figures in *RMarkdown*; it'll do it automatically. And captioning a figure is awfully easy too. In the **R** chunk below, we will load in a picture that is stored as `iheid.png` in our `figures` directory. The `include_graphics()` function is from the `{knitr}` package, that does most of the heavy lifting here. We'll label the chunk 'iheidlogo' so that we can refer back to it later, and give the figure the caption "IHEID logo". You will see that here you do not need to include the parameter `echo=FALSE`, as the code including the figure is hidden by default.

Figure 4.2: IHEID logo

4.2.2 Referencing figures

Referencing figures in the text should be done with a little reference to the chunk label so that it will always refer to the right figure number, even if you add additional figures and plots before it. To reference the IHEID logo use a backslash, at-symbol, and then in parentheses `fig:chunk-label`, like so `\@ref(fig:iheidlogo)`. Usually some descriptor like "Figure", "Fig.", "Illustration" or other is added before this reference, so that it reads something like Figure 4.2. Note that the reference is hyperlinked in the resulting PDF, so that you can click on it to take you to the page where the original figure is printed.

4.2.3 Resizing figures

It is common to resize external image files so that they fit the format of the text. The most common way to do this was already demonstrated in the code chunk for Figure 4.1 above. There we used the parameter `out.width="\\textwidth"` to, in this case, shrink the image to the width of the text, but this same parameter specification would also expand an image to fit the width of the text where possible.

Another option is the `out.extra` chunk option. This can be used to shrink or expand an image loaded from a file more specifically by specifying `"scale= "`. Here we use the graph stored in the "subdivision.pdf" file, again found in the `figures` subdirectory. The output can be found in Fig. 4.3.

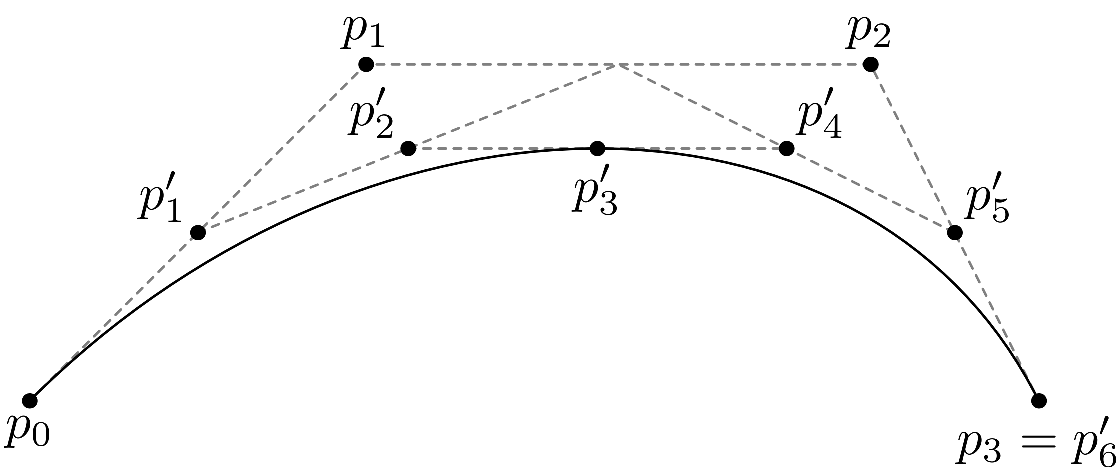


Figure 4.3: Subdiv. graph

We can also use the `out.extra` chunk option to enlarge figures, and even to rotate them any number of degrees around its axis. In Figure 4.4, we see an example where Figure 4.3 has been enlarged and flipped upside down.

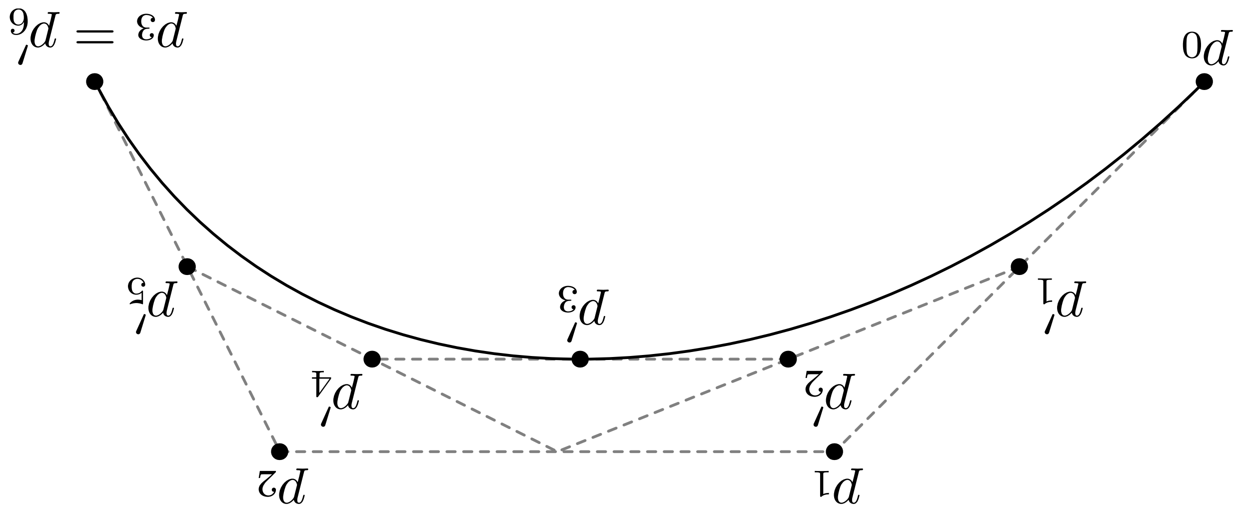


Figure 4.4: A Larger Figure, Flipped Upside Down

If you look closely at the chunk options, you will also see that two different captions have been provided. The `fig.scap` is a short caption that overrides the main caption, `fig.cap`, in the table of contents. This can be very useful where, for example, you need to describe the figure in a caption over several lines, details that do not need to be presented in the table of contents.

4.2.4 Placing figures

One thing that may be annoying is the way *RMarkdown* handles “floats” like tables and figures (it’s really LaTeX‘s fault). LaTeX will try to find the best place to put your object based on the text around it and, until you’re really, truly done writing, it is best to just leave it where it lies. There are some optional arguments specified in the options parameter of the `label` function. If you need to shift your figure around, it might be good to look here (you can click on the word ’here’) on tweaking the options argument.

Spacing out your chunks between paragraphs can help, as it can give LaTeX more options to find a suitable home for the figure or table, as LaTeX would otherwise try and keep all the text together, saving the image for later. A last trick is to write `\clearpage` directly in your *RMarkdown* document. This gives LaTeX a chance to catch up with all the ‘floats’ it has accumulated, and starts a new page.

4.3 Loading and exploring data

Sometimes it is not an existing image that must be imported, but instead you wish to create a table or plot of some data that you have imported. In this section, we're going to very quickly cover how to import internal and external data, how to manipulate and summarise the data, create plots from that data, and tabulate inferential results from that data.

4.3.1 Importing data

In some cases, the data you need might be available already in an **R** package. An example below is a very short code chunk that summarises a dataset that is built into **R**. Here it is particularly easy, as we do not even need to load the data (it is loaded by default).

```
     speed           dist       
 Min.   : 4.0   Min.   :  2.00  
 1st Qu.:12.0   1st Qu.: 26.00  
 Median :15.0   Median : 36.00  
 Mean   :15.4   Mean   : 42.98  
 3rd Qu.:19.0   3rd Qu.: 56.00  
 Max.   :25.0   Max.   :120.00  
```

Othertimes you may need to load the data first before summarising it, with the function `data()`. There are an increasing number of data packages for **R** available, including several on a range of international and development topics.

The other option is to import data that resides in a file outside of **R**. Included in this template is a file called `flights.csv`. This file includes a subset of the larger dataset of information about all flights that departed from Seattle and Portland in 2014.[2] This subset includes only Portland flights and only rows that were complete with no missing values. Merges were also done with the `airports` and `airlines` data sets in the `pnwflights14` package to get more descriptive airport and airline names. We can load in this data set using the following commands:

The data is now stored in the data frame called `flights` in the cached environment for this *RMarkdown* document in **R**. To get a better feel for the variables included in this dataset we can

[2] More information about this dataset and its **R** package is available at `https://github.com/ismayc/pnwflights14`.

use a variety of functions. Here we can see the dimensions (rows by columns) and also the names of the columns.

```
[1] 398  16
```

```
 [1] "month"        "day"          "dep_time"     "dep_delay"    "arr_time"
 [6] "arr_delay"    "carrier"      "tailnum"      "flight"       "dest"
[11] "air_time"     "distance"     "hour"         "minute"       "carrier_name"
[16] "dest_name"
```

Another good idea is to take a look at the dataset in table form. With this dataset having more than 20,000 rows, we won't explicitly show the results of the command here, so we'll use the `eval=FALSE` chunk option to make sure the following is not run when you 'knit' the document. Still, you can press the green play button at the right of the chunk to run the chunk on demand, bringing up a new tab showing the data.

4.3.2 Manipulating and summarising data

While not required, it is highly recommended you use the `dplyr` package to manipulate and summarize your data set as needed. It uses a syntax that is easy to understand using chaining or 'pipe' operations (`%>%`). Below I've created a few examples of using `dplyr` to get information about the Portland flights in 2014. The example we show here does the following:

- Selects only the `carrier_name` and `arr_delay` from the `flights` dataset and then assigns this subset to a new variable called `flights2`.
- Using `flights2`, we determine the largest arrival delay for each of the carriers.

A useful function in the `knitr` package for making nice tables in *RMarkdown* is called `kable`. It is much easier to use than manually entering values into a table by copying and pasting values into Excel or LaTeX. This again goes to show how nice reproducible documents can be! The chunk option `results="asis"` makes sure the table is produced, not the code to create the table. Tables created with the `kable()` function (in `{knitr}`) can be extended in many useful (and pretty) ways with the recommended `{kableExtra}` package.

Table 4.1: Maximum Delays by Airline

Airline	Max Arrival Delay
Alaska Airlines Inc.	181
American Airlines Inc.	72
Delta Air Lines Inc.	84
Frontier Airlines Inc.	68
Hawaiian Airlines Inc.	6
JetBlue Airways	172
SkyWest Airlines Inc.	103
Southwest Airlines Co.	315
United Air Lines Inc.	135
US Airways Inc.	347
Virgin America	22

Note that instead of adding the caption details in the chunk options, we will be adding this in the `kable()` function, which then passes this on up. The `caption.short` argument is used to include a shorter title to appear in the List of Tables. The last two options make Table 4.1 a little easier-to-read.[3]

[3] Note that we can create references/links to tables using a very similar syntax here to that with figures above. We can preface the reference with "Table" or "Tab." or so, and then create the reference with the format `\@ref(tab:chunk-label)`.

We can further look into the properties of the largest value here for Alaska Airlines Inc. To do so, we can isolate the row corresponding to the arrival delay of 70 minutes for Alaskan in our original `flights` dataset. We see that the flight occurred on January 1st and departed a little after 1:30 am on its way to Anchorage.

```
  dep_time dep_delay arr_time tailnum flight dest air_time distance
1        1        96      235  N508AS    145  ANC      194     1542
```

4.3.3 Creating plots

Once data has been loaded or imported and manipulated or filtered as required, a common task is to visualise some key dimensions of the data to inform the reader. Here the package `{ggplot2}` plays nicely with `{dplyr}` and other `{tidyverse}` packages. `{ggplot2}` produces beautiful, high-quality academic visuals, and has been extended with a huge range of add-ons for a very broad variety of visualisation styles no matter what kind of data you have.

We're going to continue playing with the `flights` dataset from Chapter 4.3.1. First, let us show how we can visualize the arrival delay of all departing flights from Portland on March 3rd against time of departure. Note that once you open the plotting function with `ggplot()`, additional elements are chained not with the pipe operator `%>%` but `+`. Considerably more help than I can offer here on how to use `ggplot()` can be found online.

Next Figure 4.5 presents a bar graph with the mean flight departure delays by airline from Portland for 2014. A table linking these carrier codes to airline names is available at `https:`

`//github.com/ismayc/pnwflights14/blob/master/data/airlines.csv`.

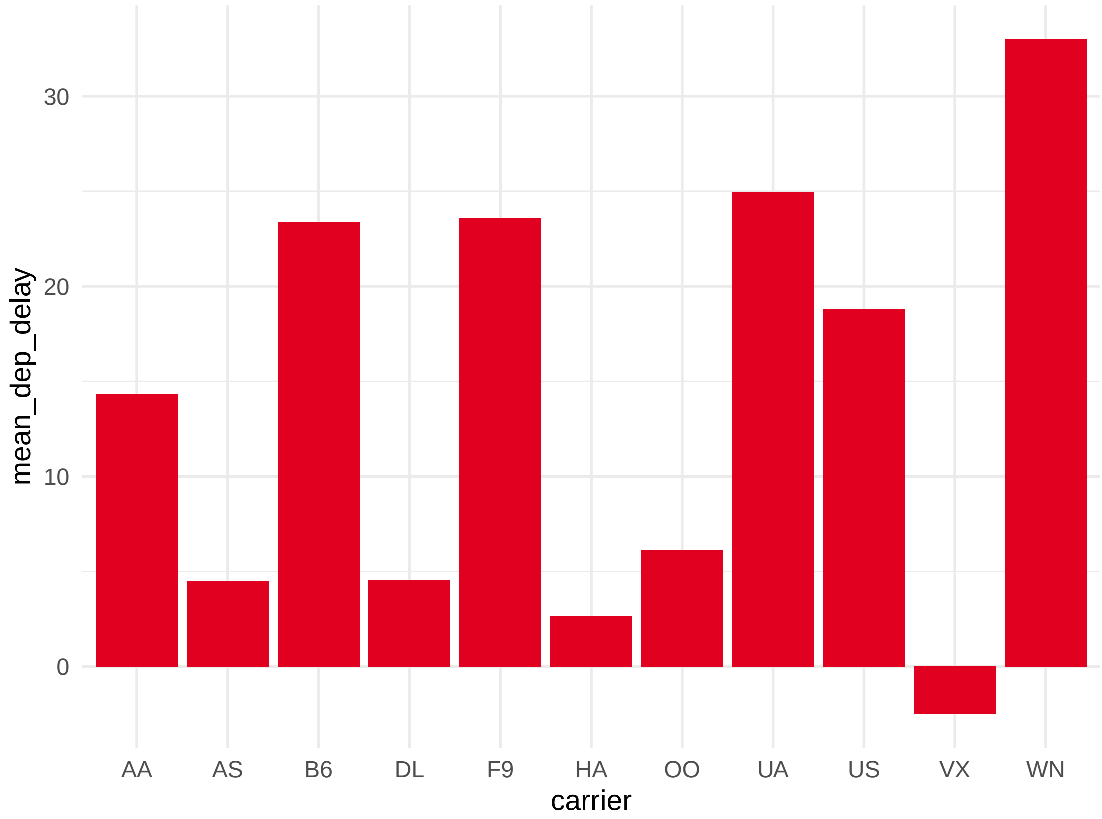
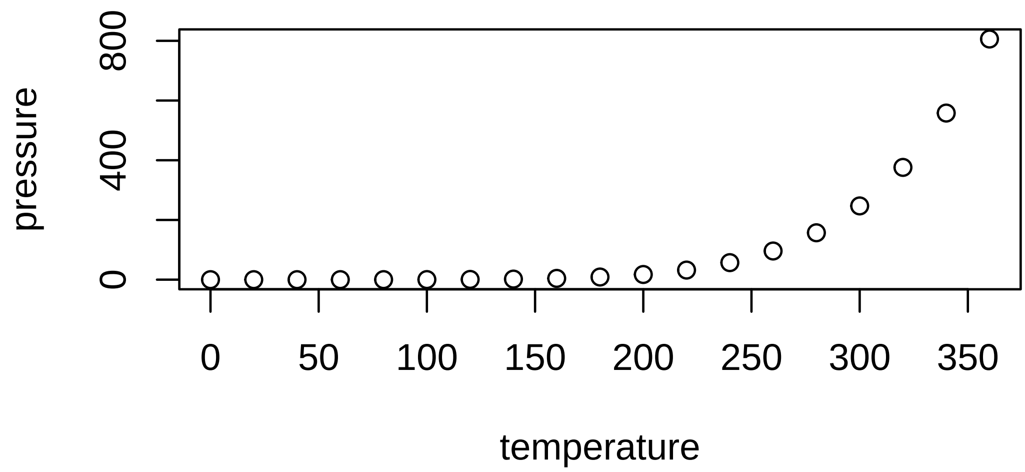


Figure 4.5: Mean Delays by Airline

You don't have to use `{ggplot2}` though. For example, here is a way to use the base **R** graphics package to produce a plot using the built-in `pressure` dataset:



4.3.4 Tabulating inferential results

Another common task researchers have is the presentation of results obtained from applying various statistical methods to their data. Since **R** makes available a very broad range of statistical methods, and all too often these output objects in different structures and formats, there is unfortunately no single package that reliably and prettily prints results. Still, I can offer a few suggestions here that cover as much as possible, in addition to `{kable}` and `{kableExtra}` mentioned above.

- `{stargazer}` for well-formatted regression tables, with multiple models side-by-side, as well as for summary statistics tables, data frames, vectors and matrices.
- `{xtable}` offers a straightforward but extensible framework.
- `{memisc}` provides tools for the management of survey data, as well as the creation of tables of summary statistics and model estimates.
- `{Hmisc}` for data description and predictive modeling.
- `{finalfit}` brings together the day-to-day functions we use to generate final results tables and plots when modelling.
- `{tableone}` i.e., description of baseline patient characteristics.

- `{flextable}` provides a framework for easily create tables for reporting and publications (PDF documents only with package `{pagedown}`).
- `{huxtable}` creates LaTeX and HTML tables with a friendly, modern interface.
- `{texreg}`
- `{apsrtable}`
- `{arsenal}`

I (James Hollway) would welcome any feedback on any other packages you find useful (more are being released all the time), and which of these worked for your purposes.

4.3.5 Tables from external data

In addition to the tables that can be automatically generated from data in **R**, you can also create tables directly using *pandoc*. This might be useful if you don't have values specifically stored in **R**, but you'd like to display them in table form.

Below is an example.

Pay careful attention to the alignment in the table and hyphens to create the rows and columns.

More information is available at `https://pandoc.org/README.html#tables`.

Table 4.2: Correlation of Inheritance Factors for Parents and Child

Factors	Correlation between Parents & Child	Inherited
Education	-0.49	Yes
Socio-Economic Status	0.28	Slight
Income	0.08	No
Family Size	0.18	Slight
Occupational Prestige	0.21	Slight

The addition of the `(\#tab:inher)` option to the end of the table caption allows us to then make a reference to Table `\@ref(tab:label)`. Note that this reference could appear anywhere throughout the document after the table has appeared.

Chapter 5

Conclusion

Appendix: The Echoes of the Code

The goal of this appendix is to echo the code you used in your thesis for a greater sense of transparency and replicability of your research. Note that `ref.labels` can be set to any label. Hence, you can filter the code you want replicated in the appendix by setting labels to the desired code chunks in the various chapters. See this excellent resource for more information.

This might be particularly useful when you perform model selection to output intermediary steps here instead of in the code to avoid cluttering your report.

Appendix: The Echoes of the Code redux

Add as many appendices as you like.

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