

Chapter udf

Axiomatic Derivations

axs.1 Introduction

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We have a semantics for the basic modal language in terms of modal models, and a notion of a **formula** being valid—true at all worlds in all models—or valid with respect to some class of models or frames—true at all worlds in all models in the class, or based on the frame. Logic usually connects such semantic characterizations of validity with a proof-theoretic notion of **derivability**. The aim is to define a notion of **derivability** in some system such that a **formula** is **derivable** iff it is valid.

The simplest and historically oldest **derivation** systems are so-called Hilbert-type or axiomatic **derivation** systems. Hilbert-type **derivation** systems for many modal logics are relatively easy to construct: they are simple as objects of metatheoretical study (e.g., to prove soundness and completeness). However, they are much harder to use to prove **formulas** in than, say, natural deduction systems.

In Hilbert-type **derivation** systems, a derivation of a **formula** is a sequence of **formulas** leading from certain axioms, via a handful of inference rules, to the **formula** in question. Since we want the **derivation** system to match the semantics, we have to guarantee that the set of **derivable** formulas are true in all models (or true in all models in which all axioms are true). We'll first isolate some properties of modal logics that are necessary for this to work: the “normal” modal logics. For normal modal logics, there are only two inference rules that need to be assumed: modus ponens and necessitation. As axioms we take all (substitution instances) of tautologies, and, depending on the modal logic we deal with, a number of modal axioms. Even if we are just interested in the class of all models, we must also count all substitution instances of **K** and **Dual** as axioms. This alone generates the minimal normal modal logic **K**.

Definition axs.1. The rule of *modus ponens* is the inference schema

$$\frac{\varphi \quad \varphi \rightarrow \psi}{\psi} \text{MP}$$

We say a **formula** ψ follows from **formulas** φ, χ by modus ponens iff $\chi \equiv \varphi \rightarrow \psi$.

Definition axs.2. The rule of *necessitation* is the inference schema

$$\frac{\varphi}{\Box\varphi} \text{ NEC}$$

We say the **formula** ψ follows from the **formulas** φ by necessitation iff $\psi \equiv \Box\varphi$.

Definition axs.3. A *derivation* from a set of axioms Σ is a sequence of **formulas** $\psi_1, \psi_2, \dots, \psi_n$, where each ψ_i is either

1. a substitution instance of a tautology, or
2. a substitution instance of a **formula** in Σ , or
3. follows from two **formulas** ψ_j, ψ_k with $j, k < i$ by modus ponens, or
4. follows from a **formula** ψ_j with $j < i$ by necessitation.

If there is such a **derivation** with $\psi_n \equiv \varphi$, we say that φ is *derivable* from Σ , in symbols $\Sigma \vdash \varphi$.

With this definition, it will turn out that the set of **derivable** formulas forms a normal modal logic, and that any **derivable formula** is true in every model in which every axiom is true. This property of **derivations** is called *soundness*. The converse, *completeness*, is harder to prove.

prf.2 Normal Modal Logics

Not every set of modal **formulas** can easily be characterized as those **formulas** derivable from a set of axioms. We want modal logics to be well-behaved. First of all, everything we can **derive** in classical propositional logic should still be **derivable**, of course taking into account that the **formulas** may now contain also \Box and \Diamond . To this end, we require that a modal logic contain all tautological instances and be closed under modus ponens.

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Definition prf.4. A *modal logic* is a set Σ of modal **formulas** which

1. contains all tautologies, and
2. is closed under substitution, i.e., if $\varphi \in \Sigma$, and $\theta_1, \dots, \theta_n$ are **formulas**, then

$$\varphi[\theta_1/p_1, \dots, \theta_n/p_n] \in \Sigma,$$

3. is closed under *modus ponens*, i.e., if φ and $\varphi \rightarrow \psi \in \Sigma$, then $\psi \in \Sigma$.

In order to use the relational semantics for modal logics, we also have to require that all **formulas** valid in all modal models are included. It turns out that this requirement is met as soon as all instances of K and DUAL are **derivable**, and whenever a **formula** φ is **derivable**, so is $\Box\varphi$. A modal logic that satisfies these conditions is called *normal*. (Of course, there are also non-normal modal logics, but the usual relational models are not adequate for them.)

Definition prf.5. A modal logic Σ is *normal* if it contains

$$\Box(p \rightarrow q) \rightarrow (\Box p \rightarrow \Box q), \quad (\text{K})$$

$$\Diamond p \leftrightarrow \neg\Box\neg p \quad (\text{DUAL})$$

and is closed under *necessitation*, i.e., if $\varphi \in \Sigma$, then $\Box\varphi \in \Sigma$.

Observe that while tautological implication is “fine-grained” enough to preserve *truth at a world*, the rule NEC only preserves *truth in a model* (and hence also validity in a frame or in a class of frames).

nml:prf:nor: **Proposition prf.6.** *Every normal modal logic is closed under rule RK,*
prop:rk

$$\frac{\varphi_1 \rightarrow (\varphi_2 \rightarrow \cdots (\varphi_{n-1} \rightarrow \varphi_n) \cdots)}{\Box\varphi_1 \rightarrow (\Box\varphi_2 \rightarrow \cdots (\Box\varphi_{n-1} \rightarrow \Box\varphi_n) \cdots)} \text{RK}$$

Proof. By induction on n : If $n = 1$, then the rule is just NEC, and every normal modal logic is closed under NEC.

Now suppose the result holds for $n - 1$; we show it holds for n .

Assume

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow \cdots (\varphi_{n-1} \rightarrow \varphi_n) \cdots) \in \Sigma$$

By the induction hypothesis, we have

$$\Box\varphi_1 \rightarrow (\Box\varphi_2 \rightarrow \cdots \Box(\varphi_{n-1} \rightarrow \varphi_n) \cdots) \in \Sigma$$

Since Σ is a normal modal logic, it contains all instances of K, in particular

$$\Box(\varphi_{n-1} \rightarrow \varphi_n) \rightarrow (\Box\varphi_{n-1} \rightarrow \Box\varphi_n) \in \Sigma$$

Using modus ponens and suitable tautological instances we get

$$\Box\varphi_1 \rightarrow (\Box\varphi_2 \rightarrow \cdots (\Box\varphi_{n-1} \rightarrow \Box\varphi_n) \cdots) \in \Sigma. \quad \square$$

nml:prf:nor: **Proposition prf.7.** *Every normal modal logic Σ contains $\neg\Diamond\perp$.*
prop:notDiamondBot

Problem prf.1. Prove **Proposition prf.7**.

Proposition prf.8. *Let $\varphi_1, \dots, \varphi_n$ be formulas. Then there is a smallest modal logic Σ containing all instances of $\varphi_1, \dots, \varphi_n$.*

Proof. Given $\varphi_1, \dots, \varphi_n$, define Σ as the intersection of all normal modal logics containing all instances of $\varphi_1, \dots, \varphi_n$. The intersection is non-empty as $\text{Frm}(\mathcal{L})$, the set of all **formulas**, is such a modal logic. \square

Definition prf.9. The smallest normal modal logic containing $\varphi_1, \dots, \varphi_n$ is called a *modal system* and denoted by $\mathbf{K}\varphi_1 \dots \varphi_n$. The smallest normal modal logic is denoted by \mathbf{K} .

prf.3 Derivations and Modal Systems

We first define what a **derivation** is for normal modal logics. Roughly, a **derivation** is a sequence of **formulas** in which every **element** is either (a substitution instance of) one of a number of *axioms*, or follows from previous **elements** by one of a few inference rules. For normal modal logics, all instances of tautologies, \mathbf{K} , and DUAL count as axioms. This results in the modal system \mathbf{K} , the smallest normal modal logic. We may wish to add additional axioms to obtain other systems, however. The rules are always modus ponens MP and necessitation NEC .

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Definition prf.10. Given a modal system $\mathbf{K}\varphi_1 \dots \varphi_n$ and a **formula** ψ we say that ψ is *derivable* in $\mathbf{K}\varphi_1 \dots \varphi_n$, written $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi$, if and only if there are **formulas** χ_1, \dots, χ_k such that $\chi_k = \psi$ and each χ_i is either a tautological instance, or an instance of one of \mathbf{K} , DUAL , $\varphi_1, \dots, \varphi_n$, or it follows from previous **formulas** by means of the rules MP or NEC .

The following proposition allows us to show that $\psi \in \Sigma$ by exhibiting a Σ -**derivation** of ψ .

Proposition prf.11. $\mathbf{K}\varphi_1 \dots \varphi_n = \{\psi : \mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi\}$.

Proof. We use induction on the length of **derivations** to show that $\{\psi : \mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi\} \subseteq \mathbf{K}\varphi_1 \dots \varphi_n$.

If the **derivation** of ψ has length 1, it contains a single **formula**. That **formula** cannot follow from previous formulas by MP or NEC , so must be a tautological instance, an instance of \mathbf{K} , DUAL , or an instance of one of $\varphi_1, \dots, \varphi_n$. But $\mathbf{K}\varphi_1 \dots \varphi_n$ contains these as well, so $\psi \in \mathbf{K}\varphi_1 \dots \varphi_n$.

If the **derivation** of ψ has length > 1 , then ψ may in addition be obtained by MP or NEC from **formulas** not occurring as the last line in the **derivation**. If ψ follows from χ and $\chi \rightarrow \psi$ (by MP), then χ and $\chi \rightarrow \psi \in \mathbf{K}\varphi_1 \dots \varphi_n$ by induction hypothesis. But every modal logic is closed under modus ponens, so $\psi \in \mathbf{K}\varphi_1 \dots \varphi_n$. If $\psi \equiv \Box\chi$ follows from χ by NEC , then $\chi \in \mathbf{K}\varphi_1 \dots \varphi_n$ by induction hypothesis. But every normal modal logic is closed under NEC , so $\psi \in \mathbf{K}\varphi_1 \dots \varphi_n$.

The converse inclusion follows by showing that $\Sigma = \{\psi : \mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi\}$ is a normal modal logic containing all the instances of $\varphi_1, \dots, \varphi_n$, and the observation that $\mathbf{K}\varphi_1 \dots \varphi_n$ is, by definition, the smallest such logic.

1. Every tautology ψ is a tautological instance, so $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi$, so Σ contains all tautologies.
2. If $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \chi$ and $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \chi \rightarrow \psi$, then $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi$: Combine the **derivation** of χ with that of $\chi \rightarrow \psi$, and add the line ψ . The last line is justified by MP. So Σ is closed under modus ponens.
3. If ψ has a **derivation**, then every substitution instance of ψ also has a derivation: apply the substitution to every **formula** in the **derivation**. (Exercise: prove by induction on the length of **derivations** that the result is also a correct **derivation**). So Σ is closed under uniform substitution. (We have now established that Σ satisfies all conditions of a modal logic.)
4. We have $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \mathbf{K}$, so $\mathbf{K} \in \Sigma$.
5. We have $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \text{DUAL}$, so $\text{DUAL} \in \Sigma$.
6. If $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \chi$, the additional line $\Box\chi$ is justified by NEC. Consequently, Σ is closed under NEC. Thus, Σ is normal. \square

prf.4 Proofs in \mathbf{K}

nml:prf:prk:
sec In order to practice proofs in the smallest modal system, we show the valid **formulas** on the left-hand side of ?? can all be given \mathbf{K} -proofs.

Proposition prf.12. $\mathbf{K} \vdash \Box\varphi \rightarrow \Box(\psi \rightarrow \varphi)$

Proof.

- | | | |
|--|--------------|-----------|
| 1. $\varphi \rightarrow (\psi \rightarrow \varphi)$ | TAUT | |
| 2. $\Box(\varphi \rightarrow (\psi \rightarrow \varphi))$ | NEC, 1 | |
| 3. $\Box(\varphi \rightarrow (\psi \rightarrow \varphi)) \rightarrow (\Box\varphi \rightarrow \Box(\psi \rightarrow \varphi))$ | \mathbf{K} | |
| 4. $\Box\varphi \rightarrow \Box(\psi \rightarrow \varphi)$ | MP, 2, 3 | \square |

Proposition prf.13. $\mathbf{K} \vdash \Box(\varphi \wedge \psi) \rightarrow (\Box\varphi \wedge \Box\psi)$

Proof.

1. $(\varphi \wedge \psi) \rightarrow \varphi$ TAUT
2. $\Box((\varphi \wedge \psi) \rightarrow \varphi)$ NEC
3. $\Box((\varphi \wedge \psi) \rightarrow \varphi) \rightarrow (\Box(\varphi \wedge \psi) \rightarrow \Box\varphi)$ K
4. $\Box(\varphi \wedge \psi) \rightarrow \Box\varphi$ MP, 2, 3
5. $(\varphi \wedge \psi) \rightarrow \psi$ TAUT
6. $\Box((\varphi \wedge \psi) \rightarrow \psi)$ NEC
7. $\Box((\varphi \wedge \psi) \rightarrow \psi) \rightarrow (\Box(\varphi \wedge \psi) \rightarrow \Box\psi)$ K
8. $\Box(\varphi \wedge \psi) \rightarrow \Box\psi$ MP, 6, 7
9. $(\Box(\varphi \wedge \psi) \rightarrow \Box\varphi) \rightarrow$
 $((\Box(\varphi \wedge \psi) \rightarrow \Box\psi) \rightarrow$
 $(\Box(\varphi \wedge \psi) \rightarrow (\Box\varphi \wedge \Box\psi)))$ TAUT
10. $(\Box(\varphi \wedge \psi) \rightarrow \Box\psi) \rightarrow$
 $(\Box(\varphi \wedge \psi) \rightarrow (\Box\varphi \wedge \Box\psi))$ MP, 4, 9
11. $\Box(\varphi \wedge \psi) \rightarrow (\Box\varphi \wedge \Box\psi)$ MP, 8, 10.

Note that the **formula** on line 9 is an instance of the tautology

$$(p \rightarrow q) \rightarrow ((p \rightarrow r) \rightarrow (p \rightarrow (q \wedge r))). \quad \square$$

Proposition prf.14. $\mathbf{K} \vdash (\Box\varphi \wedge \Box\psi) \rightarrow \Box(\varphi \wedge \psi)$

Proof.

1. $\varphi \rightarrow (\psi \rightarrow (\varphi \wedge \psi))$ TAUT
2. $\Box(\varphi \rightarrow (\psi \rightarrow (\varphi \wedge \psi)))$ NEC, 1
3. $\Box(\varphi \rightarrow (\psi \rightarrow (\varphi \wedge \psi))) \rightarrow (\Box\varphi \rightarrow \Box(\psi \rightarrow (\varphi \wedge \psi)))$ K
4. $\Box\varphi \rightarrow \Box(\psi \rightarrow (\varphi \wedge \psi))$ MP, 2, 3
5. $\Box(\psi \rightarrow (\varphi \wedge \psi)) \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi))$ K
6. $(\Box\varphi \rightarrow \Box(\psi \rightarrow (\varphi \wedge \psi))) \rightarrow$
 $(\Box(\psi \rightarrow (\varphi \wedge \psi)) \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi))) \rightarrow$
 $(\Box\varphi \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi)))$ TAUT
7. $(\Box(\psi \rightarrow (\varphi \wedge \psi)) \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi))) \rightarrow$
 $(\Box\varphi \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi)))$ MP, 4, 6
8. $\Box\varphi \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi))$ MP, 5, 7
9. $(\Box\varphi \rightarrow (\Box\psi \rightarrow \Box(\varphi \wedge \psi))) \rightarrow$
 $((\Box\varphi \wedge \Box\psi) \rightarrow \Box(\varphi \wedge \psi))$ TAUT
10. $(\Box\varphi \wedge \Box\psi) \rightarrow \Box(\varphi \wedge \psi)$ MP, 8, 9

The **formulas** on lines 6 and 9 are instances of the tautologies

$$(p \rightarrow q) \rightarrow ((q \rightarrow r) \rightarrow (p \rightarrow r))$$

$$(p \rightarrow (q \rightarrow r)) \rightarrow ((p \wedge q) \rightarrow r) \quad \square$$

Proposition prf.15. $\mathbf{K} \vdash \neg\Box p \rightarrow \Diamond\neg p$

Proof.

- | | | |
|-----|--|-----------|
| 1. | $\Diamond\neg p \leftrightarrow \neg\Box\neg\neg p$ | DUAL |
| 2. | $(\Diamond\neg p \leftrightarrow \neg\Box\neg\neg p) \rightarrow$
$(\neg\Box\neg\neg p \rightarrow \Diamond\neg p)$ | TAUT |
| 3. | $\neg\Box\neg\neg p \rightarrow \Diamond\neg p$ | MP, 1, 2 |
| 4. | $\neg\neg p \rightarrow p$ | TAUT |
| 5. | $\Box(\neg\neg p \rightarrow p)$ | NEC, 4 |
| 6. | $\Box(\neg\neg p \rightarrow p) \rightarrow (\Box\neg\neg p \rightarrow \Box p)$ | K |
| 7. | $(\Box\neg\neg p \rightarrow \Box p)$ | MP, 5, 6 |
| 8. | $(\Box\neg\neg p \rightarrow \Box p) \rightarrow (\neg\Box p \rightarrow \neg\Box\neg\neg p)$ | TAUT |
| 9. | $\neg\Box p \rightarrow \neg\Box\neg\neg p$ | MP, 7, 8 |
| 10. | $(\neg\Box p \rightarrow \neg\Box\neg\neg p) \rightarrow$
$((\neg\Box\neg\neg p \rightarrow \Diamond\neg p) \rightarrow (\neg\Box p \rightarrow \Diamond\neg p))$ | TAUT |
| 11. | $(\neg\Box\neg\neg p \rightarrow \Diamond\neg p) \rightarrow (\neg\Box p \rightarrow \Diamond\neg p)$ | MP, 9, 10 |
| 12. | $\neg\Box p \rightarrow \Diamond\neg p$ | MP, 3, 11 |

The **formulas** on lines 8 and 10 are instances of the tautologies

$$(p \rightarrow q) \rightarrow (\neg q \rightarrow \neg p)$$

$$(p \rightarrow q) \rightarrow ((q \rightarrow r) \rightarrow (p \rightarrow r)). \quad \square$$

Problem prf.2. Find **derivations** in **K** for the following **formulas**:

1. $\Box\neg p \rightarrow \Box(p \rightarrow q)$
2. $(\Box p \vee \Box q) \rightarrow \Box(p \vee q)$
3. $\Diamond p \rightarrow \Diamond(p \vee q)$

prf.5 Derived Rules

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sec Finding and writing **derivations** is obviously difficult, cumbersome, and repetitive. For instance, very often we want to pass from $\varphi \rightarrow \psi$ to $\Box\varphi \rightarrow \Box\psi$, i.e., apply rule RK. That requires an application of NEC, then recording the proper instance of K, then applying MP. Passing from $\varphi \rightarrow \psi$ and $\psi \rightarrow \chi$ to $\varphi \rightarrow \chi$ requires recording the (long) tautological instance

$$(\varphi \rightarrow \psi) \rightarrow ((\psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi))$$

and applying MP twice. Often we want to replace a sub-**formula** by a formula we know to be equivalent, e.g., $\Diamond\varphi$ by $\neg\Box\neg\varphi$, or $\neg\neg\varphi$ by φ . So rather than write out the actual **derivation**, it is more convenient to simply record why the intermediate steps are **derivable**. For this purpose, let us collect some facts about **derivability**.

Proposition prf.16. *If $\mathbf{K} \vdash \varphi_1, \dots, \mathbf{K} \vdash \varphi_n$, and ψ follows from $\varphi_1, \dots, \varphi_n$ by propositional logic, then $\mathbf{K} \vdash \psi$.*

Proof. If ψ follows from $\varphi_1, \dots, \varphi_n$ by propositional logic, then

$$\varphi_1 \rightarrow (\varphi_2 \rightarrow \dots (\varphi_n \rightarrow \psi) \dots)$$

is a tautological instance. Applying MP n times gives a **derivation** of ψ . \square

We will indicate use of this proposition by PL.

Proposition prf.17. *If $\mathbf{K} \vdash \varphi_1 \rightarrow (\varphi_2 \rightarrow \dots (\varphi_{n-1} \rightarrow \varphi_n) \dots)$ then $\mathbf{K} \vdash \Box \varphi_1 \rightarrow (\Box \varphi_2 \rightarrow \dots (\Box \varphi_{n-1} \rightarrow \Box \varphi_n) \dots)$.*

Proof. By induction on n , just as in the proof of **Proposition prf.6**. \square

We will indicate use of this proposition by RK. Let's illustrate how these results help establishing **derivability** results more easily.

Proposition prf.18. $\mathbf{K} \vdash (\Box \varphi \wedge \Box \psi) \rightarrow \Box(\varphi \wedge \psi)$

Proof.

1. $\mathbf{K} \vdash \varphi \rightarrow (\psi \rightarrow (\varphi \wedge \psi))$ TAUT
2. $\mathbf{K} \vdash \Box \varphi \rightarrow (\Box \psi \rightarrow \Box(\varphi \wedge \psi))$ RK, 1
3. $\mathbf{K} \vdash (\Box \varphi \wedge \Box \psi) \rightarrow \Box(\varphi \wedge \psi)$ PL, 2 \square

Proposition prf.19. *If $\mathbf{K} \vdash \varphi \leftrightarrow \psi$ and $\mathbf{K} \vdash \chi[\varphi/q]$ then $\mathbf{K} \vdash \chi[B/q]$*

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prop:rewriting*

Proof. Exercise. \square

Problem prf.3. Prove **Proposition prf.19** by proving, by induction on the complexity of χ , that if $\mathbf{K} \vdash \varphi \leftrightarrow \psi$ then $\mathbf{K} \vdash \chi[\varphi/q] \leftrightarrow \chi[\psi/q]$.

This proposition comes in handy especially when we want to convert \diamond into \Box (or vice versa), or remove double negations inside a **formula**. In what follows, we will mark applications of **Proposition prf.19** by “ φ for ψ ” whenever we re-write a **formula** $\chi(\psi)$ for $\chi(\varphi)$. In other words, “ φ for ψ ” abbreviates:

$$\begin{array}{l} \vdash \chi(\varphi) \\ \vdash \varphi \leftrightarrow \psi \\ \vdash \chi(\psi) \quad \text{by Proposition prf.19} \end{array}$$

For instance:

Proposition prf.20. $\mathbf{K} \vdash \neg \Box p \rightarrow \diamond \neg p$

Proof.

1. $\mathbf{K} \vdash \diamond \neg p \leftrightarrow \neg \Box \neg \neg p$ DUAL
2. $\mathbf{K} \vdash \neg \Box \neg \neg p \rightarrow \diamond \neg p$ PL, 1
3. $\mathbf{K} \vdash \neg \Box p \rightarrow \diamond \neg p$ p for $\neg \neg p$ \square

In the above [derivation](#), the final step “ p for $\neg\neg p$ ” is short for

$$\begin{array}{l} \mathbf{K} \vdash \neg\Box\neg\neg p \rightarrow \Diamond\neg p \\ \mathbf{K} \vdash \neg\neg p \leftrightarrow p \quad \text{TAUT} \\ \mathbf{K} \vdash \neg\Box p \rightarrow \Diamond\neg p \quad \text{by Proposition prf.19} \end{array}$$

The roles of $\chi(q)$, φ , and ψ in [Proposition prf.19](#) are played here, respectively, by $\neg\Box q \rightarrow \Diamond\neg p$, $\neg\neg p$, and p .

When a [formula](#) contains a sub-formula $\neg\Diamond\varphi$, we can replace it by $\Box\neg\varphi$ using [Proposition prf.19](#), since $\mathbf{K} \vdash \neg\Diamond\varphi \leftrightarrow \Box\neg\varphi$. We’ll indicate this and similar replacements simply by “ $\Box\neg$ for $\neg\Diamond$.”

The following proposition justifies that we can establish [derivability](#) results schematically. E.g., the previous proposition does not just establish that $\mathbf{K} \vdash \neg\Box p \rightarrow \Diamond\neg p$, but $\mathbf{K} \vdash \neg\Box\varphi \rightarrow \Diamond\neg\varphi$ for arbitrary φ .

Proposition prf.21. *If φ is a substitution instance of ψ and $\mathbf{K} \vdash \psi$, then $\mathbf{K} \vdash \varphi$.*

Proof. It is tedious but routine to verify (by induction on the length of the [derivation](#) of ψ) that applying a substitution to an entire [derivation](#) also results in a correct [derivation](#). Specifically, substitution instances of tautological instances are themselves tautological instances, substitution instances of instances of DUAL and K are themselves instances of DUAL and K, and applications of MP and NEC remain correct when substituting [formulas](#) for [propositional variables](#) in both premise(s) and conclusion. \square

prf.6 More Proofs in K

[nml:prf:mpr:sec](#) Let’s see some more examples of [derivability](#) in \mathbf{K} , now using the simplified method introduced in [section prf.5](#).

Proposition prf.22. $\mathbf{K} \vdash \Box(\varphi \rightarrow \psi) \rightarrow (\Diamond\varphi \rightarrow \Diamond\psi)$

Proof.

1. $\mathbf{K} \vdash (\varphi \rightarrow \psi) \rightarrow (\neg\psi \rightarrow \neg\varphi)$ PL
2. $\mathbf{K} \vdash \Box(\varphi \rightarrow \psi) \rightarrow (\Box\neg\psi \rightarrow \Box\neg\varphi)$ RK, 1
3. $\mathbf{K} \vdash (\Box\neg\psi \rightarrow \Box\neg\varphi) \rightarrow (\neg\Box\neg\varphi \rightarrow \neg\Box\neg\psi)$ TAUT
4. $\mathbf{K} \vdash \Box(\varphi \rightarrow \psi) \rightarrow (\neg\Box\neg\varphi \rightarrow \neg\Box\neg\psi)$ PL, 2, 3
5. $\mathbf{K} \vdash \Box(\varphi \rightarrow \psi) \rightarrow (\Diamond\varphi \rightarrow \Diamond\psi)$ \Diamond for $\neg\Box\neg$. \square

Proposition prf.23. $\mathbf{K} \vdash \Box\varphi \rightarrow (\Diamond(\varphi \rightarrow \psi) \rightarrow \Diamond\psi)$

Proof.

1. $\mathbf{K} \vdash \varphi \rightarrow (\neg\psi \rightarrow \neg(\varphi \rightarrow \psi))$ TAUT
2. $\mathbf{K} \vdash \Box\varphi \rightarrow (\Box\neg\psi \rightarrow \Box\neg(\varphi \rightarrow \psi))$ RK, 1
3. $\mathbf{K} \vdash \Box\varphi \rightarrow (\neg\Box\neg(\varphi \rightarrow \psi) \rightarrow \neg\Box\neg\psi)$ PL, 2
4. $\mathbf{K} \vdash \Box\varphi \rightarrow (\Diamond(\varphi \rightarrow \psi) \rightarrow \Diamond\psi)$ \Diamond for $\neg\Box\neg$. \square

Proposition prf.24. $\mathbf{K} \vdash (\diamond\varphi \vee \diamond\psi) \rightarrow \diamond(\varphi \vee \psi)$

Proof.

1. $\mathbf{K} \vdash \neg(\varphi \vee \psi) \rightarrow \neg\varphi$ TAUT
2. $\mathbf{K} \vdash \Box\neg(\varphi \vee \psi) \rightarrow \Box\neg\varphi$ RK, 1
3. $\mathbf{K} \vdash \neg\Box\neg\varphi \rightarrow \neg\Box\neg(\varphi \vee \psi)$ PL, 2
4. $\mathbf{K} \vdash \diamond\varphi \rightarrow \diamond(\varphi \vee \psi)$ \diamond for $\neg\Box\neg$
5. $\mathbf{K} \vdash \diamond\psi \rightarrow \diamond(\varphi \vee \psi)$ similarly
6. $\mathbf{K} \vdash (\diamond\varphi \vee \diamond\psi) \rightarrow \diamond(\varphi \vee \psi)$ PL, 4, 5. □

Proposition prf.25. $\mathbf{K} \vdash \diamond(\varphi \vee \psi) \rightarrow (\diamond\varphi \vee \diamond\psi)$

Proof.

1. $\mathbf{K} \vdash \neg\varphi \rightarrow (\neg\psi \rightarrow \neg(\varphi \vee \psi))$ TAUT
2. $\mathbf{K} \vdash \Box\neg\varphi \rightarrow (\Box\neg\psi \rightarrow \Box\neg(\varphi \vee \psi))$ RK
3. $\mathbf{K} \vdash \Box\neg\varphi \rightarrow (\neg\Box\neg(\varphi \vee \psi) \rightarrow \neg\Box\neg\psi)$ PL, 2
4. $\mathbf{K} \vdash \neg\Box\neg(\varphi \vee \psi) \rightarrow (\Box\neg\varphi \rightarrow \neg\Box\neg\psi)$ PL, 3
5. $\mathbf{K} \vdash \neg\Box\neg(\varphi \vee \psi) \rightarrow (\neg\neg\Box\neg\psi \rightarrow \neg\Box\neg\varphi)$ PL, 4
6. $\mathbf{K} \vdash \diamond(\varphi \vee \psi) \rightarrow (\neg\Box\neg\psi \rightarrow \diamond\varphi)$ \diamond for $\neg\Box\neg$
7. $\mathbf{K} \vdash \diamond(\varphi \vee \psi) \rightarrow (\diamond\psi \vee \diamond\varphi)$ PL, 6. □

Problem prf.4. Show that the following *derivability* claims hold:

1. $\mathbf{K} \vdash \diamond\neg\perp \rightarrow (\Box\varphi \rightarrow \diamond\varphi)$;
2. $\mathbf{K} \vdash \Box(\varphi \vee \psi) \rightarrow (\diamond\varphi \vee \Box\psi)$;
3. $\mathbf{K} \vdash (\diamond\varphi \rightarrow \Box\psi) \rightarrow \Box(\varphi \rightarrow \psi)$.

prf.7 Dual Formulas

Definition prf.26. Each of the *formulas* T, B, 4, and 5 has a *dual*, denoted by a subscripted diamond, as follows:

[nml:prf:dua:](#)
[sec](#)
[nml:prf:dua:](#)
[def:duals](#)

$$\begin{aligned}
 p &\rightarrow \diamond p && (\mathbf{T}_\diamond) \\
 \diamond\Box p &\rightarrow p && (\mathbf{B}_\diamond) \\
 \diamond\diamond p &\rightarrow \diamond p && (4_\diamond) \\
 \diamond\Box p &\rightarrow \Box p && (5_\diamond)
 \end{aligned}$$

Each of the above dual *formulas* is obtained from the corresponding *formula* by substituting $\neg p$ for p , contraposing, replacing $\neg\Box\neg$ by \diamond , and replacing $\neg\diamond\neg$ by \Box . D, i.e., $\Box\varphi \rightarrow \diamond\varphi$ is its own dual in that sense.

Problem prf.5. Show that for each *formula* φ in **Definition prf.26**: $\mathbf{K} \vdash \varphi \leftrightarrow \varphi_\diamond$.

prf.8 Proofs in Modal Systems

nml:prf:prs:sec We now come to proofs in systems of modal logic other than **K**.

nml:prf:prs:prop:S5facts **Proposition prf.27.** *The following provability results obtain:*

1. **KT5** \vdash B;
2. **KT5** \vdash 4;
3. **KDB4** \vdash T;
4. **KB4** \vdash 5;
5. **KB5** \vdash 4;
6. **KT** \vdash D.

nml:prf:prs:prop:S5facts-KT-D

Proof. We exhibit proofs for each.

1. **KT5** \vdash B:

1. **KT5** \vdash $\Diamond\varphi \rightarrow \Box\Diamond\varphi$ 5
2. **KT5** \vdash $\varphi \rightarrow \Diamond\varphi$ T_\Diamond
3. **KT5** \vdash $\varphi \rightarrow \Box\Diamond\varphi$ PL.

2. **KT5** \vdash 4:

1. **KT5** \vdash $\Diamond\Box\varphi \rightarrow \Box\Diamond\Box\varphi$ 5 with $\Box\varphi$ for p
2. **KT5** \vdash $\Box\varphi \rightarrow \Diamond\Box\varphi$ T_\Diamond with $\Box\varphi$ for p
3. **KT5** \vdash $\Box\varphi \rightarrow \Box\Diamond\Box\varphi$ PL, 1, 2
4. **KT5** \vdash $\Diamond\Box\varphi \rightarrow \Box\varphi$ 5_\Diamond
5. **KT5** \vdash $\Box\Diamond\Box\varphi \rightarrow \Box\Box\varphi$ RK, 4
6. **KT5** \vdash $\Box\varphi \rightarrow \Box\Box\varphi$ PL, 3, 5.

3. **KDB4** \vdash T:

1. **KDB4** \vdash $\Diamond\Box\varphi \rightarrow \varphi$ B_\Diamond
2. **KDB4** \vdash $\Box\Box\varphi \rightarrow \Diamond\Box\varphi$ D with $\Box\varphi$ for p
3. **KDB4** \vdash $\Box\Box\varphi \rightarrow \varphi$ PL1, 2
4. **KDB4** \vdash $\Box\varphi \rightarrow \Box\Box\varphi$ 4
5. **KDB4** \vdash $\Box\varphi \rightarrow \varphi$ PL, 1, 4.

4. **KB4** \vdash 5:

1. **KB4** \vdash $\Diamond\varphi \rightarrow \Box\Diamond\Diamond\varphi$ B with $\Diamond\varphi$ for p
2. **KB4** \vdash $\Diamond\Diamond\varphi \rightarrow \Diamond\varphi$ 4_\Diamond
3. **KB4** \vdash $\Box\Diamond\Diamond\varphi \rightarrow \Box\Diamond\varphi$ RK, 2
4. **KB4** \vdash $\Diamond\varphi \rightarrow \Box\Diamond\varphi$ PL, 1, 3.

5. **KB5** \vdash 4:

1. **KB5** $\vdash \Box\varphi \rightarrow \Box\Diamond\Box\varphi$ B with $\Box\varphi$ for p
2. **KB5** $\vdash \Diamond\Box\varphi \rightarrow \Box\varphi$ 5_\Diamond
3. **KB5** $\vdash \Box\Diamond\Box\varphi \rightarrow \Box\Box\varphi$ RK, 2
4. **KB5** $\vdash \Box\varphi \rightarrow \Box\Box\varphi$ PL, 1, 3.

6. **KT** \vdash D:

1. **KT** $\vdash \Box\varphi \rightarrow \varphi$ T
2. **KT** $\vdash \varphi \rightarrow \Diamond\varphi$ T_\Diamond
3. **KT** $\vdash \Box\varphi \rightarrow \Diamond\varphi$ PL, 1, 2 □

Definition prf.28. Following tradition, we define **S4** to be the system **KT4**, and **S5** the system **KTB4**.

The following proposition shows that the classical system **S5** has several equivalent axiomatizations. This should not surprise, as the various combinations of axioms all characterize equivalence relations (see ??).

Proposition prf.29. **KTB4 = KT5 = KDB4 = KDB5.**

*nml:prf:prs:
prop:S5*

Proof. Exercise. □

Problem prf.6. Prove **Proposition prf.29**.

prf.9 Soundness

A **derivation** system is called sound if everything that can be **derived** is valid. When considering modal systems, i.e., **derivations** where in addition to K we can use instances of some **formulas** $\varphi_1, \dots, \varphi_n$, we want every **derivable** formula to be true in any model in which $\varphi_1, \dots, \varphi_n$ are true.

*nml:prf:snd:
sec*

Theorem prf.30 (Soundness Theorem). *If every instance of $\varphi_1, \dots, \varphi_n$ is valid in the classes of models $\mathcal{C}_1, \dots, \mathcal{C}_n$, respectively, then $\mathbf{K}\varphi_1 \dots \varphi_n \vdash \psi$ implies that ψ is valid in the class of models $\mathcal{C}_1 \cap \dots \cap \mathcal{C}_n$.*

*nml:prf:snd:
thm:soundness*

Proof. By induction on length of proofs. For brevity, put $\mathcal{C} = \mathcal{C}_1 \cap \dots \cap \mathcal{C}_n$.

1. Induction Basis: If ψ has a proof of length 1, then it is either a tautological instance, an instance of K, or of DUAL, or an instance of one of $\varphi_1, \dots, \varphi_n$. In the first case, ψ is valid in \mathcal{C} , since tautological instance are valid in *any* class of models, by ??. Similarly in the second case, by ?? and ??. Finally in the third case, since ψ is valid in \mathcal{C}_i and $\mathcal{C} \subseteq \mathcal{C}_i$, we have that ψ is valid in \mathcal{C} as well by ??.

2. Inductive step: Suppose ψ has a proof of length $k > 1$. If ψ is a tautological instance or an instance of one of $\varphi_1, \dots, \varphi_n$, we proceed as in the previous step. So suppose ψ is obtained by MP from previous formulas $\chi \rightarrow \psi$ and χ . Then $\chi \rightarrow \psi$ and χ have proofs of length $< k$, and by inductive hypothesis they are valid in \mathcal{C} . By ??, ψ is valid in \mathcal{C} as well. Finally suppose ψ is obtained by NEC from χ (so that $\psi = \Box\chi$). By inductive hypothesis, χ is valid in \mathcal{C} , and by ?? so is ψ . \square

prf.10 Showing Systems are Distinct

nml:prf:dis:
sec

In [section prf.8](#) we saw how to prove that two systems of modal logic are in fact the same system. [Theorem prf.30](#) allows us to show that two modal systems Σ and Σ' are distinct, by finding a formula φ such that $\Sigma' \vdash \varphi$ that fails in a model of Σ .

Proposition prf.31. $\mathbf{KD} \subsetneq \mathbf{KT}$

Proof. This is the syntactic counterpart to the semantic fact that all reflexive relations are serial. To show $\mathbf{KD} \subseteq \mathbf{KT}$ we need to see that $\mathbf{KD} \vdash \psi$ implies $\mathbf{KT} \vdash \psi$, which follows from $\mathbf{KT} \vdash \mathbf{D}$, as shown in [Proposition prf.27\(6\)](#). To show that the inclusion is proper, by Soundness ([Theorem prf.30](#)), it suffices to exhibit a model of \mathbf{KD} where \mathbf{T} , i.e., $\Box p \rightarrow p$, fails (an easy task left as an exercise), for then by Soundness $\mathbf{KD} \not\vdash \Box p \rightarrow p$. \square

Proposition prf.32. $\mathbf{KB} \neq \mathbf{K4}$.

Proof. We construct a symmetric model where some instance of 4 fails; since obviously the instance is derivable for $\mathbf{K4}$ but not in \mathbf{KB} , it will follow $\mathbf{K4} \not\subseteq \mathbf{KB}$. Consider the symmetric model \mathfrak{M} of [Figure prf.1](#). Since the model is symmetric, \mathbf{K} and \mathbf{B} are true in \mathfrak{M} (by ?? and ??, respectively). However, $\mathfrak{M}, w_1 \not\vdash \Box p \rightarrow \Box\Box p$. \square

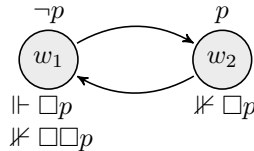


Figure prf.1: A symmetric model falsifying an instance of 4.

nml:prf:dis:
nml:prf:dis:
fig:Bnot4
thm:KTBnot45

Theorem prf.33. $\mathbf{KTB} \not\vdash 4$ and $\mathbf{KTB} \not\vdash 5$.

Proof. By ?? we know that all instances of \mathbf{T} and \mathbf{B} are true in every reflexive symmetric model (respectively). So by soundness, it suffices to find a reflexive symmetric model containing a world at which some instance of 4 fails, and similarly for 5. We use the same model for both claims. Consider the symmetric, reflexive model in [Figure prf.2](#). Then $\mathfrak{M}, w_1 \not\vdash \Box p \rightarrow \Box\Box p$, so 4 fails at w_1 . Similarly, $\mathfrak{M}, w_2 \not\vdash \Diamond \neg p \rightarrow \Box \Diamond \neg p$, so the instance of 5 with $\varphi = \neg p$ fails at w_2 . \square

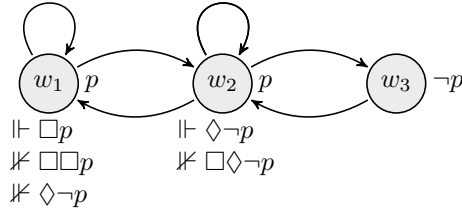


Figure prf.2: The model for **Theorem prf.33**.

nml:prf:dis:
fig:KTBnot45

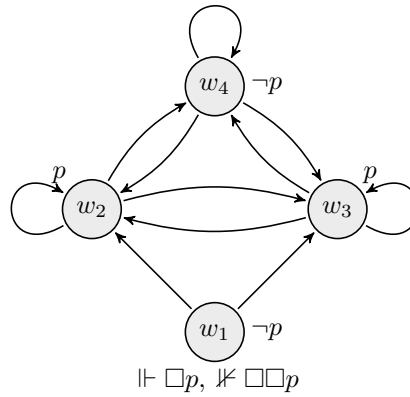


Figure prf.3: The model for **Theorem prf.34**.

nml:prf:dis:
fig:KD5not4
nml:prf:dis:
thm:KD5not4

Theorem prf.34. $\text{KD5} \neq \text{KT4} = \text{S4}$.

Proof. By ?? we know that all instances of D and 5 are true in all serial euclidean models. So it suffices to find a serial euclidean model containing a world at which some instance of 4 fails. Consider the model of **Figure prf.3**, and notice that $\mathfrak{M}, w_1 \not\models \Box p \rightarrow \Box \Box p$. \square

Problem prf.7. Give an alternative proof of **Theorem prf.34** using a model with 3 worlds.

Problem prf.8. Provide a single reflexive transitive model showing that both $\text{KT4} \not\models \text{B}$ and $\text{KT4} \not\models 5$.

prf.11 Derivability from a Set of Formulas

In **section prf.8** we defined a notion of provability of a formula in a system Σ . We now extend this notion to provability in Σ from formulas in a set Γ .

nml:prf:prg:
sec

nml:prf:prg:
defn:Gamma proves

Definition prf.35. A formula φ is **derivable** in a system Σ from a set of formulas Γ , written $\Gamma \vdash_{\Sigma} \varphi$ if and only if there are $\psi_1, \dots, \psi_n \in \Gamma$ such that $\Sigma \vdash \psi_1 \rightarrow (\psi_2 \rightarrow \dots (\psi_n \rightarrow \varphi) \dots)$.

prf.12 Properties of Derivability

nml:prf:prp:
sec
nml:prf:prp:
prop:derivabilityfacts

Proposition prf.36. Let Σ be a modal system and Γ a set of modal formulas. The following properties hold:

1. Monotonicity: If $\Gamma \vdash_{\Sigma} \varphi$ and $\Gamma \subseteq \Delta$ then $\Delta \vdash_{\Sigma} \varphi$;
nml:prf:prp:
prop:derivabilityfacts-monotonicity
2. Reflexivity: If $\varphi \in \Gamma$ then $\Gamma \vdash_{\Sigma} \varphi$;
nml:prf:prp:
prop:derivabilityfacts-reflexivity
3. Cut: If $\Gamma \vdash_{\Sigma} \varphi$ and $\Delta \cup \{\varphi\} \vdash_{\Sigma} \psi$ then $\Gamma \cup \Delta \vdash_{\Sigma} \psi$;
nml:prf:prp:
prop:derivabilityfacts-cut
4. Deduction theorem: $\Gamma \cup \{\psi\} \vdash_{\Sigma} \varphi$ if and only if $\Gamma \vdash_{\Sigma} \psi \rightarrow \varphi$;
nml:prf:prp:
prop:derivabilityfacts-deduction
5. $\Gamma \vdash_{\Sigma} \varphi_1$ and \dots and $\Gamma \vdash_{\Sigma} \varphi_n$ and $\varphi_1 \rightarrow (\varphi_2 \rightarrow \dots (\varphi_n \rightarrow \psi) \dots)$ is a tautological instance, then $\Gamma \vdash_{\Sigma} \psi$.
nml:prf:prp:
prop:derivabilityfacts-ruleT

The proof is an easy exercise. Part (5) of **Proposition prf.36** gives us that, for instance, if $\Gamma \vdash_{\Sigma} \varphi \vee \psi$ and $\Gamma \vdash_{\Sigma} \neg\varphi$, then $\Gamma \vdash_{\Sigma} \psi$. Also, in what follows, we write $\Gamma, \varphi \vdash_{\Sigma} \psi$ instead of $\Gamma \cup \{\varphi\} \vdash_{\Sigma} \psi$.

Definition prf.37. A set Γ is *deductively closed* relatively to a system Σ if and only if $\Gamma \vdash_{\Sigma} \varphi$ implies $\varphi \in \Gamma$.

prf.13 Consistency

nml:prf:con:
sec

Consistency is an important property of sets of formulas. A set of formulas is inconsistent if a contradiction, such as \perp , is derivable from it; and otherwise consistent. If a set is inconsistent, its formulas cannot all be true in a model at a world. For the completeness theorem we prove the converse: every consistent set is true at a world in a model, namely in the “canonical model.”

Definition prf.38. A set Γ is *consistent* relatively to a system Σ or, as we will say, Σ -consistent, if and only if $\Gamma \not\vdash_{\Sigma} \perp$.

So for instance, the set $\{\Box(p \rightarrow q), \Box p, \neg\Box q\}$ is consistent relatively to propositional logic, but not **K**-consistent. Similarly, the set $\{\Diamond p, \Box\Diamond p \rightarrow q, \neg q\}$ is not **K5**-consistent.

nml:prf:con:
prop:consistencyfacts

Proposition prf.39. Let Γ be a set of formulas. Then:

nml:prf:con:
prop:consistencyfacts-b

1. Γ is Σ -consistent if and only if there is some formula φ such that $\Gamma \not\vdash_{\Sigma} \varphi$.
2. $\Gamma \vdash_{\Sigma} \varphi$ if and only if $\Gamma \cup \{\neg\varphi\}$ is not Σ -consistent.

3. If Γ is Σ -consistent, then for any formula φ , either $\Gamma \cup \{\varphi\}$ is Σ -consistent or $\Gamma \cup \{\neg\varphi\}$ is Σ -consistent. nml:prf:con:
prop:consistencyfacts-c

Proof. These facts follow easily using classical propositional logic. We give the argument for (3). Proceed contrapositively and suppose neither $\Gamma \cup \{\varphi\}$ nor $\Gamma \cup \{\neg\varphi\}$ is Σ -consistent. Then by (2), both $\Gamma, \varphi \vdash_{\Sigma} \perp$ and $\Gamma, \neg\varphi \vdash_{\Sigma} \perp$. By the deduction theorem $\Gamma \vdash_{\Sigma} \varphi \rightarrow \perp$ and $\Gamma \vdash_{\Sigma} \neg\varphi \rightarrow \perp$. But $(\varphi \rightarrow \perp) \rightarrow ((\neg\varphi \rightarrow \perp) \rightarrow \perp)$ is a tautological instance, hence by Proposition prf.36(5), $\Gamma \vdash_{\Sigma} \perp$. \square

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Bibliography