


8. Note however, that in (Nelken and Francez, 1998), coordination is handled in a direct and straightforward manner, without any need for type-shifting.

9. We cannot use the abbreviation \( \varphi(I, x) \) in the representation of the universally quantified sentence.

References


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Notes

1. We stick to this terminological distinction, reserving the term meaning representation for the ILQ translation of NL terms, the term interpretation for the model-theoretic analysis of ILQ formulae, and semantics/meaning for the combination of the two.

2. In (Nelken and Francez, 1998), we consider two variants of ILQ. The language introduced here corresponds to the weaker variant considered there.

3. Note that the indicative and interrogative formulae do not exhaust the range of ILQ formulae.

4. Note that we use the square semantic brackets in two different roles, both for the denoting the extension and intension of ILQ formulae and for denoting the meaning of NL expressions, but with different subscripts.

5. The determiner the is interpreted here, for the sake of uniformity, using the Russellian approach, where $\exists x[\varphi]$ means there exists a unique $x$ s.t. $\varphi$. More modern interpretations, based on anaphoric reference and familiarity, could also be used.

6. The details of applying temporal modification at the VP level are discussed in (Pratt and Francez, 1997).

7. Note, however that in (Nelken and Francez, 1998) this difference disappears by interpreting type $t$ over a bilattice instead of a two-valued logic.
indicative formulae were equivalent. However, equivalence between interrogative formulae is a stronger notion. For example, (113) is equivalent to our question, since it induces the same partition on the set of possible worlds.

(113) During which meeting did Mary not kiss John?

6 Conclusion

In this paper we have shown how a formal treatment of temporal questions may be derived by combining the approach of (Pratt and Francez, 1998) to temporal preposition phrases and that of (Groenendijk and Stokhof, 1984) to the semantics of questions. We have endeavored to combine the two frameworks as seamlessly as possible. Our account provides a systematic account of the meanings of basic temporal questions. It is our belief that this account may form the basis of further work relating the two fields, opening the way for the analysis of additional and more complex temporal questions. Questions on states may be interpreted according to similar methods, based on the analysis of states of (Pratt and Francez, 1997). In addition, embedded and intensional questions, as well as the dynamics of discourse may be analyzed.

Another related research direction which we are currently pursuing is the design of an NL interface to a temporal database. In contrast with traditional databases, temporal databases store time-dependent data. They are receiving increasing interest in the field of Computer Science, including the design of specialized temporal query languages for storing and extracting data in these databases (see e.g. (Snodgrass, 1995)). The addition of the temporal dimension to a formal query language typically makes the expression of queries much more complex for the average user. To counter this problem, we are developing a NL interface. Using this interface, users will be able to express temporal queries in NL, and have these semi-automatically translated into a formal query language. The design of this interface is closely based on the analysis of temporal questions developed here.
Definition 6 (Entailment) If $\psi?, \varphi? \text{ are of type (s,t), then:}$

$\psi? \models_M \varphi?$ iff for any $\sigma$, $\forall w \in W : \llbracket \psi? \rrbracket_{M,w,\sigma} \subseteq \llbracket \varphi? \rrbracket_{M,w,\sigma}$.

Based on this definition, we give some example entailments between temporal questions and (96).

- Question (96) entails the yes/no question (110).

  (110) Did Mary kiss John?

  (111) $?x[I, x] \models ?[\exists x_0 [\text{kiss(Mary, John)}(x_0) \land \text{time}(x_0) \subseteq I]]$.

  The reason for this is that (96) induces a finer partition on the set of possible worlds. The yes/no question partitions the set of possible worlds into two blocks, those in which Mary did kiss John and those in which she did not. Each equivalence class of the partition induced by the first question is wholly included in one of these two blocks of possible worlds. Formally, let $w$ be a possible world. Then, $\llbracket ?x[I, x] \rrbracket_{M,w,\sigma} \subseteq \llbracket ?[\exists x_0 [\text{kiss(Mary, John)}(x_0) \land \text{time}(x_0) \subseteq I]] \rrbracket_{M,w,\sigma}$.

- For similar reasons, (96) is entailed by (112).

  (112) During which dull meeting did Mary kiss John?

5.3 Equivalence

Equivalence between interrogative formulae is defined as equivalence of the intensions for each possible world $w$, i.e. entailment in both directions.

Definition 7 (Equivalence) $\psi? \equiv_M \varphi?$ iff for any $\sigma$, $\forall w \in W :$

$\llbracket \psi? \rrbracket_{M,w,\sigma} = \llbracket \varphi? \rrbracket_{M,w,\sigma}$.

The relation of equivalence between a pair of interrogative formulae may be defined either directly as an equivalence of their intensions, or indirectly as double entailment. Both results amount to the same relation. In fact, we have tacitly been taking advantage of equivalence in deriving the ILQ representations of questions, where we have used an equivalence between subsequent steps in the derivation. This was justified since the embedded
When did Mary kiss John?

Recall that calendrical tNs are viewed as referring to events. Because there is no restriction on the kind of event being asked for by when questions, there is a subtle point about their answers. An exact answer is viewed as an answer according to the answerhood relation. For example (106) is such an answer.

Mary kissed John exactly between 1600 and 1600 and 10 seconds.

However, NL answers are seldom that exact. An answer that is not exact is not considered a full answer according to the answerhood relation. The reason for this is that as shown above, if \( x_0 \) is an event included in the extension of a when question, then any event \( x_1 \) which includes it is also included in the extension. Thus giving an event (or a calendrical item) as an answer to a when question implies that any larger event is also in the extension (as long as the larger event is still included within the temporal context). By the same token, an inexact indicative sentence may be true in two worlds even if they belong to different equivalence classes. For example, (107) is true both in a world where (108) is true and in one where (109) is true. These two possible worlds clearly belong to different equivalence classes (assuming the completeness implicature). Thus (107) may be seen only as a partial answer.

Mary kissed John on Monday.

Mary kissed John on Monday morning.

Mary kissed John on Monday afternoon.

5.2 Interrogative Entailment

Entailment of interrogative formulae is defined as follows: \( \psi \) entails \( \varphi \) in a structure \( M \) iff for all possible worlds \( w \) of \( M \), the intension of \( \psi \) in \( w \) is included in the intension of \( \varphi \) in \( w \). Note the difference between this definition and the regular definition of indicative entailment, due to the difference in basic types. In indicative entailment, the intension of one formula should be included in the intension of the other. Here, this condition should hold for each possible world. Intuitively, an interrogative formula entails another iff every block in the partition induced by the first is included in a block of the partition induced by the second one. Formally:
• Similarly, (99) is an answer to the question for the same reason. Its meaning is a complete block in the partition induced by the question. Formally, this is written as in (100).\(^9\)

(99) Mary kissed John during every meeting.

(100) \(\forall x[\text{MEETING}(x) \land \text{time}(x) \subseteq I \rightarrow \exists x_0[\text{KISS(MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq \text{time}(x)] \models ?x[\varphi(I, x)]\).

• An indicative sentence such as (101), in which the quantification over meetings is existential, is not an answer to the question, since its intension is not wholly included in any one of the equivalence classes.

(101) Mary kissed John during a meeting.

To see this, consider a structure \(M\) with two possible worlds: \(w_1\) and \(w_2\). Assume Mary kissed John during one meeting in \(w_1\) and during two meetings in \(w_2\). Clearly, (101) is true in both worlds. Thus \(\[\exists x[\varphi(I, x)]\]_{M, \sigma} = \{w_1, w_2\}\). Now, \(w_1\) and \(w_2\) belong to different equivalence classes, with respect to the equivalence relation induced by the question. Thus we have:

(102) \(\[?x[\varphi(I, x)]\]_{M, w_1, \sigma} \neq \[?x[\varphi(I, x)]\]_{M, w_2, \sigma}\).

This implies that for no possible world is the intension of \(\exists x[\varphi(I, x)]\) included in that of \(?x[\varphi(I, x)]\).

• Any other proposition which is wholly included in one of the equivalence classes may also serve as an answer. For example, (103) is intuitively such an answer, making the plausible assumption that dull meetings are in fact meetings. However, in order to formally be considered an answer, this NL sentence must carry with it a completeness implicature, as in (104). Without it, the sentence only specifies that Mary kissed John during dull meetings, but remains silent as to whether she did so during additional meetings. For pragmatic reasons it is reasonable to assume such an implicature. With its addition, the intension of the sentence is wholly included in one of the equivalence classes induced by the question.

(103) Mary kissed John during every dull meeting.

(104) Mary kissed John only during every dull meeting.

• A when question such as (1), repeated here as (105) may be answered in a similar fashion, by specifying those events during which Mary kissed John.
In terms of the partition into equivalence classes induced by an interrogative formula $\psi_2^!$, $\psi_1^!$ is a possible answer to $\psi_2^!$ iff the set of possible worlds that is the intension of $\psi_1^!$, is wholly included in one of the equivalence classes.

For any structure $M$, $\psi_1^! = \psi_2^!$ for any structure $M$. 

In terms of the partition into equivalence classes induced by an interrogative formula $\psi_2^!$, $\psi_1^!$ is a possible answer to $\psi_2^!$ iff the set of possible worlds that is the intension of $\psi_1^!$, is wholly included in one of the equivalence classes. The definition of answerhood is given in terms of ILQ formulae. The answerhood relation between ILQ formulae induces a similar relation on NL sentences. Here are several examples of this relation between indicative sentences and our prototypical question (52), repeated here as (96).

(96) **During which meeting did Mary kiss John?**

- By definition, a contradiction answers any question. This is seen as follows. Let $\psi^!$ denote some contradiction, and let $\varphi(I, x)$ be the abbreviation of (57). For any structure $M$ and assignment $\sigma$, $[i^! \psi^!]_{M, w, \sigma} = \emptyset$. Let $w$ be any possible world. Then, trivially, $[i^! \psi^!]_{M, w, \sigma} \subseteq [i^! \exists x[\varphi(I, x)]]_{M, w, \sigma}$. For answerhood, as for classical indicative entailment, no notion of relevance is formally required between the question and its answer.

- Sentence (97) is an answer to (96). Formally, this is written as in (98). Note that the answerhood relation is verified relative to all assignments of an interval to $I$.

(97) **Mary kissed John during no meeting.**

(98) $\neg \exists x[\varphi(I, x)] \models [\exists x[\varphi(I, x)]]_{M, w, \sigma}$.

The answerhood relation holds because for any structure $M$, one of the equivalence classes in the partition induced by the meaning of the interrogative sentence is that block of possible worlds in which there is no meeting during which Mary kissed John. For any assignment $\sigma$, let $w$ be a possible world such that $w \in [i^! \exists x[\varphi(I, x)]]_{M, w, \sigma}$. If there is no such world, then $[i^! \exists x[\varphi(I, x)]]_{M, w, \sigma} = \emptyset$. And therefore, by a similar argument to the previous item, (98) is proved. Otherwise, $[i^! \exists x[\varphi(I, x)]]_{M, w, \sigma} \subseteq [i^! \exists x[\varphi(I, x)]]_{M, w, \sigma}$, since any possible world $w'$ which belongs to $[i^! \exists x[\varphi(I, x)]]_{M, \sigma}$ also belongs to the equivalence class of $w$, i.e. $w' \in [i^! \exists x[\varphi(I, x)]]_{M, w, \sigma}$. A finer analysis might associate an existential presupposition with the question, ruling out such an answer, which contradicts this presupposition.
5 Semantic notions

After presenting the meanings of temporal questions we turn to studying some semantic notions. In (Groenendijk and Stokhof, 1997), the following semantic notions are defined: answerhood, entailment and equivalence. Answerhood is a formal relation between a pair of formulae, an indicative one and an interrogative one. This relation formally captures the intuitive notion of the indicative formula being a possible (not necessarily true) answer to the interrogative one. Entailment between questions is a less intuitive notion. However, it is exactly the relation used in the common practice of reducing one question to another, which is common in both scientific and everyday thought. Once such an entailment relation is defined, equivalence between questions may be defined as mutual entailment. Using these notions, one may formally verify for a pair of two sentences whether their meanings stand in one of these relations, e.g. whether a given sentence provides an answer to a given question. Following (Groenendijk and Stokhof, 1997), we use the same symbol $\models$ for both answerhood and interrogative entailment as well as the familiar indicative entailment. The meanings of both indicative and interrogative sentences is a function of two variables $P$ and $I$. When relating a pair of sentences according to these semantic relations we substitute $\top$ for $P$ and instantiate the temporal context $I$ to some value, the same value for both sentences.

5.1 Answers

Answerhood is defined as a relation between an indicative proposition and an interrogative, as follows. An indicative formula $\psi!$ of type $\mathbf{t}$ is an answer to an interrogative formula $\varphi?$ of type $(s, \mathbf{t})$, iff its intension (a set of possible worlds) is completely included in one of the equivalence classes of the partition induced by the interrogative formula in any possible world. Formally:

\textbf{Definition 5 (Answerhood)}

1. If $\psi!$ is of type $\mathbf{t}$, and $\varphi?$ is of type $(s, \mathbf{t})$, then:
   \[ \psi! \models_M \varphi? \text{ iff for any } \sigma, \text{ there is a possible world } w \in W \text{ such that} \]
\[ \lambda y_0[a(\lambda x_0[kiss(sue, bill)(x_0) \land time(x_0) \subseteq time(y_0), P)])]_2. \]

Applying Definition 4 a third time replaces the occurrence of \( \sqcap \) in the result with regular conjunction. Carrying out the pseudo-application yields:

\[
(93) \quad \lambda P\lambda I[\text{which}(\lambda x_2[\text{meeting}(x_2) \land time(x_2) \subseteq I], \lambda y_1[P[time(y_1)])]]
\]

\[
2\lambda P_0\lambda I_0[a(\lambda x_1[time(x_1) \subseteq I],
\lambda y_0[a(\lambda x_0[kiss(mary, john)(x_0) \land time(x_0) \subseteq time(y_0), P_0)])]
\]

\[
a(\lambda x_1[time(x_1) \subseteq I],
\lambda y_0[a(\lambda x_0[kiss(sue, bill)(x_0) \land time(x_0) \subseteq time(y_0), P)])]
\]

\[
\lambda P\lambda I[\text{which}(\lambda x_2[\text{meeting}(x_2) \land time(x_2) \subseteq I],
\lambda y_1[a(\lambda x_1[time(x_1) \subseteq time(y_1)],
\lambda y_0[a(\lambda x_0[kiss(mary, john)(x_0) \land time(x_0) \subseteq time(y_0), P)])]
\]

\[
a(\lambda x_1[time(x_1) \subseteq time(y_1)],
\lambda y_0[a(\lambda x_0[kiss(sue, bill)(x_0) \land time(x_0) \subseteq time(y_0), P)])]
\]

We may simplify this formula by getting rid of the event variables \( x_1 \), the only function of which is to relate the kissing events \( x_0 \) with the meeting event \( x_2 \):

\[
(94) \quad \lambda P\lambda I[\text{which}(\lambda x_1[\text{meeting}(x_1) \land time(x_1) \subseteq I],
\lambda y_0[a(\lambda x_0[kiss(mary, john)(x_0) \land time(x_0) \subseteq time(y_0), P)])]
\]

\[
a(\lambda x_0[kiss(sue, bill)(x_0) \land time(x_0) \subseteq time(y_0), P)].
\]

Instantiating \( P \) to \( \top \) and expanding the abbreviations \textit{which} and \textit{a} yields:

\[
(95) \quad \lambda I? x[\text{meeting}(x) \land time(x) \subseteq I \land
\exists x_1[kiss(mary, john)(x_1) \land time(x_1) \subseteq time(x)] \land
\exists x_2[kiss(sue, bill)(x_2) \land time(x_2) \subseteq time(x)].
\]

This formula yields the required interpretation of the conjoined question, its extension is a function of the toi \( I \), which asks for meeting events \( x \) such that the event-time of \( x \) is included in \( I \), and there are kissing events of Mary’s kissing John and Sue kissing Bill within this event-time.
During which meeting Mary kissed John then and Sue kissed Bill then?

During which meeting Mary kissed John then and Sue kissed Bill then?

Notice that this conjunction is not standard conjunction of type $t$ terms, since the meaning of each conjunct "gappy"-sentence denotes a function, accepting a type $(e, t)$ and a type $i$ argument. To overcome this, we employ the notion of generalized conjunction of (Keenan and Faltz, 1985; Partee and Rooth, 1983). Using this notion, any two elements of the same type $(a, t)$, for any type $a$ may be conjoined, using an operation denoted by $\sqcap$, and defined as follows (writing functions in ordered pair notation):

**Definition 4**

$$X \sqcap Y = \begin{cases} X \sqcap Y & \text{if } X, Y \text{ are of type } t \\ \{ \langle z, x \sqcap y \rangle \mid \langle z, x \rangle \in X, \langle z, y \rangle \in Y \} & \text{otherwise.} \end{cases}$$

Adding the connective $\sqcap$ to ILQ, we may now assign and the following polymorphic meaning. For any variables $x, y$ of the same type $a$ ending in type $t$.

$$[\text{conj}] = \lambda x \lambda y [x \sqcap y].$$

Thus the conjunction above may be translated as follows:

$$[\text{pp} \text{During which meeting}] (2[\text{conj}]) ([\text{Mary kissed John then}], [\text{Sue kissed Bill then}]) \sqcap$$

Since the types of each of the (generalized) conjuncts ends in $t$, we may apply Definition 4 twice, as in the standard analysis of generalized conjunction, "unifying" both the two $P$ variables and the two $I$ variables as follows:

$$[\text{pp} \text{During which meeting}] (2 \lambda P \lambda I [a(\lambda x_1 [\text{time}(x_1) \subseteq I], \lambda y_0 [a(\lambda x_0 [\text{KISS(MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0), P)]) \sqcap a(\lambda x_1 [\text{time}(x_1) \subseteq I],$$
During which meeting did Mary kiss John and during which meeting did Sue kiss Bill?

The meanings of these two interrogative sentences are different. (86) asks for a single meeting, during which both kissing events occurred. On the other hand, (87) asks for a pair of meetings during each of which a kissing event occurred. The analysis of (87) in the framework of G&S turns out to be rather complex. The straightforward approach of defining the intension of the conjunction as the intersection of the intensions of each question works correctly for conjunction but yields an erroneous interpretation for disjunction as shown in (Groenendijk and Stokhof, 1989). Roughly, the reason for this is that the G&S interpretation views questions as inducing partitions on the set of possible worlds. Interpreting conjunction as inducing intersection on the equivalence classes of the two partitions yields a new, finer partition. However, applying set-union to equivalence classes of partitions does not yield a further partition. In (Groenendijk and Stokhof, 1989) this problem is solved (in a non-temporal context) by proposing a more complex analysis of conjunctions/disjunctions of questions, based on type-shifting operations. For the sake of simplicity, we will not pursue the details of this analysis here, focusing only on examples of the form of (86).9

We therefore confine our attention to (86). Intuitively, such a question should be answered by giving the set of meetings during which both kissing events occurred. Other than being included in the same meeting, there is no further requirement on the temporal relation between the two meetings. Recall that we have employed a simplifying assumption of applying the meaning of tPPs at the sentential level instead of the VP level. We may therefore derive the meanings of such sentences by direct temporal modification of the conjunction of sentences. Were we to suspend the simplifying assumption, assuming temporal modification operates at the VP level, this method would no longer be possible. This is because the tPP has wider scope than the conjoined sentence, and thus may not be applied to the VPs. We would then employ indirect construction, deriving first the meaning of the gappy conjuncts, modified by then, conjoin them, and the pseudo-apply the meaning of the tPP. The need for indirect construction is not dependent on the interrogative nature of the sentence. The same need arises for a temporally-modified conjunction of indicative sentences. We retain the simplifying assumption, but illustrate this process by using the indirect construction method. Thus instead of conjoining sentences, we conjoin “gappy sentences” with the particle then as in (88).
Such questions are ambiguous. This ambiguity can be characterized in terms of a scope ambiguity of the tPP and the wh-word when. For example, on one reading (82) asks for a time during which every meeting included a kissing event. A second reading (which is more readily obtained by replacing every by each) may be viewed as giving during every meeting wider scope, and asking for every meeting, when Mary kissed John during that meeting. Deriving the meaning of the second reading in a compositional manner is notoriously difficult. In (Nelken and Francez, 1998) we show how straightforward application of direct and indirect construction may be used to give a uniform analysis of both kinds of readings in the context of general non-temporal questions. However, this analysis is based on a different overall approach to the interpretation of questions than the G&S interpretation used here. We will therefore concentrate on the first reading here, always giving the interrogative tPP wider scope. We may thus always derive their meaning by direct construction, with the logical ordering of the tPPs corresponding to that of the tPPs in the sentence. We may therefore compute (85). Similar meaning representations may be derived for the other examples.

(85) \[ [s, t] \text{When did Mary kiss John during every meeting?} = \\
[\text{tPP when}] (2[s, \text{Mary kissed John then during every meeting}])_2 = \\
\lambda P \lambda I[\text{which}(\lambda x_2[\text{time}(x_2) \subseteq I], \lambda y_1[P(\text{time}(y_1))]) \\
(2\lambda P_0 \lambda I_0[\text{every}(\lambda x_1[\text{MEETING}(x_1) \land \text{time}(x_1) \subseteq I_0], \\
\lambda y_0[\alpha(\lambda x_0[\text{KISS}(\text{MARY}, \text{JOHN})(x_0) \land \\
\text{time}(x_0) \subseteq \text{time}(y_0)], P_0)])])_2 = \\
\lambda P \lambda I[\text{which}(\lambda x_2[\text{time}(x_2) \subseteq I], \\
\lambda y_1[\text{every}(\lambda x_1[\text{MEETING}(x_1) \land \text{time}(x_1) \subseteq \text{time}(y_1)], \\
\lambda y_0[\alpha(\lambda x_0[\text{KISS}(\text{MARY}, \text{JOHN})(x_0) \land \\
\text{time}(x_0) \subseteq \text{time}(y_0)], \\
P)])])].
\]

We now turn our attention to questions involving coordination.

4.8 Coordination

Coordination may be combined with temporal questions in two ways, depending on the relative scopes of the conjunction/disjunction and the interrogative tPP, as illustrated by the following two examples:

(86) During which meeting did Mary kiss John and Sue kiss Bill?
Indirect construction proceeds as follows. First we apply the meaning of the tPP every day to the meaning of the gappy sentence with the particle then as shown in (79). The result may be simplified in a similar manner to that described above, yielding (80). The final meaning is obtained by pseudo-applying the remaining tPP to the result, yielding (81), which is indeed the same meaning as that obtained by direct construction for the original sentence.

(79) $\begin{align*}
[S, \text{Mary kissed John then during the meeting}] &= \\
[\text{tPP during the meeting}]^2 [S, \text{Mary kissed John then}]_2 = \\
&\lambda \forall x_1 \forall x_2 \forall y_1 \forall y_2 A \left[ \left( \text{MEETING}(x_2) \land \text{time}(x_2) \subseteq I \right) \land \\
&\left( \text{MEETING}(x_1) \land \text{time}(x_1) \subseteq \text{time}(y_1) \right) \land \\
&\left( \text{MEETING}(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0) \right) \land \\
&\left( P \right) \right] .
\end{align*}$

(80) $\begin{align*}
[S, \text{Mary kissed John then during the meeting}] &= \\
&\lambda \forall x_1 \forall x_2 \forall y_1 \forall y_2 A \left[ \left( \text{MEETING}(x_2) \land \text{time}(x_2) \subseteq I \right) \land \\
&\left( \text{MEETING}(x_1) \land \text{time}(x_1) \subseteq \text{time}(y_1) \right) \land \\
&\left( \text{MEETING}(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0) \right) \land \\
&\left( P \right) \right] .
\end{align*}$

(81) $\begin{align*}
[S, \text{Mary kissed John every day during the meeting}] &= \\
[\text{tPP every day}]^2 [S, \text{Mary kissed John then during the meeting}]_2 = \\
&\lambda \forall x_1 \forall x_2 \forall y_1 \forall y_2 A \left[ \left( \text{MEETING}(x_2) \land \text{time}(x_2) \subseteq I \right) \land \\
&\left( \text{MEETING}(x_1) \land \text{time}(x_1) \subseteq \text{time}(y_1) \right) \land \\
&\left( \text{MEETING}(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0) \right) \land \\
&\left( P \right) \right] .
\end{align*}$

By the intermediate simplification step of getting rid of the event argument $x_1$, this construction method may be seen to lead to exactly the same results as the method of (Pratt and Francez, 1998), which simply allows the application of the tPPs in any order. Thus from a practical point of view, there is no reason to prefer one over the other. Applying the same methods, we may derive the meanings of questions containing a single interrogative and one or more indicative tPPs:

(82) When did Mary kiss John during every meeting?

(83) When did Mary kiss John during one summer?

(84) When did Mary kiss John after they met?
plied to when questions. The two construction methods may lead to different results when multiple tPPs are cascaded, as shown in the next sub-section.

4.7 Cascaded indicative and interrogative tPPs

We now turn to consider sentences with multiple tPPs. A sentence modified by multiple indicative tPPs may be constructed by step-by-step pseudo-application of the meanings of the tPPs as shown above. Sentences containing multiple tPPs may sometimes be interpreted not according to the original order of tPPs in the sentence. For example, consider (76). This sentence is interpreted according to the order of the tPPs in the sentence by giving the tPP every day higher scope over during the meeting, meaning that for every day there is a meeting during which Mary kissed John. Reversing the order of the tPPs in the sentence as in (77) does not change its meaning. This is because this logical order of the tPPs is the only plausible one, assuming that meetings are included within days and not vice-versa. The reverse ordering would yield the degenerate reading that for the unique meeting in the toi, Mary kissed John during every day included within that meeting. This is a degenerate reading, since meetings typically do not contain days.

(76) Mary kissed John during the meeting every day.
(77) Mary kissed John every day during the meeting.

In order to account for this phenomenon, when encountering multiple tPPs, (Pratt and Francez, 1997) allows them to be pseudo-applied at any order. The degenerate readings are ruled out not by semantic means, but by world-knowledge factors. Here we subscribe to the same freedom in the logical order of applying tPPs but implement it slightly differently using the direct and indirect construction methods. Direct construction applies the meanings of tPPs in the same order in which they appear in the sentence as described above. Indirect construction works by replacing the first tPP with the particle then, applying the second tPP and then applying the first tPP to the result. To illustrate the two methods, we will use direct construction on (76), as shown in (78) and indirect construction on the reversed sentence (77), which should yield the same results.

(78) \[ \text{[S, Mary kissed John during the meeting every day]} = \]
\[ \text{tPP every day}[2\text{Mary kissed John during the meeting}]_2 = \]
\[ \lambda P\forall I[\text{every}(\lambda x_2[\text{day}(x_2) \land \text{time}(x_2) \subseteq I]), \]
\[ \lambda y_1[\text{the}(\lambda x_1[\text{meeting}(x_1) \land \text{time}(x_1) \subseteq \text{time}(y_1))], \]

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the result. However, whereas the construction of the meaning of a gappy sentence involves a free variable, which is subsequently abstracted over, no such free variable is used in applying this method in the temporal domain.

We implement this method in the temporal domain for both indicative and interrogative temporally modified sentences. For example, consider once again our prototypical question (52). First, we form the meaning of the gappy sentence with the particle then as in (67). We then pseudo-apply the meaning of the interrogative tPP during which meeting as shown in (73).

\[
\text{[S]: During which meeting did Mary kiss John?] = \\
\text{[wh-IP: During which meeting[2[S, Mary kissed John then]]2] =} \\
\lambda P \lambda I[\text{which}(\lambda x_2[\text{MEETING}(x_2) \land \text{time}(x_2) \subseteq I], \lambda y_1[P(\text{time}(y_1))]) \\
(2\lambda P_0 \lambda I_0[\text{a}((\lambda x_1[\text{time}(x_1) \subseteq I_0], \\
\lambda y_0[a(\lambda x_0[\text{KISS(MARY, JOHN)}(x_0) \land \\
\text{time}(x_0) \subseteq \text{time}(y_0)), P_0))])]_2 = \\
\lambda P \lambda I[\text{which}(\lambda x_2[\text{MEETING}(x_2) \land \text{time}(x_2) \subseteq I], \\
\lambda y_1[a(\lambda x_1[\text{time}(x_1) \subseteq \text{time}(y_1)], \\
\lambda y_0[a(\lambda x_0[\text{KISS(MARY, JOHN)}(x_0) \land \\
\text{time}(x_0) \subseteq \text{time}(y_0)), P)])])].
\]

Looking at this formula, we see that the temporal relation between kissing events \(x_0\) and meetings \(x_2\) is recorded indirectly through another event \(x_1\). The formula ‘asks’ for meetings \(x_2\), the event-time of which includes an event \(x_1\), the event-time of which includes a kissing event. Notice that the only contribution of the event \(x_1\) is enforcing this temporal relation between \(x_0\) and \(x_2\). Thus we may simplify the formula by getting rid of \(x_1\), and relating the event-times of \(x_0\) and \(x_2\) directly, yielding an equivalent formula (after renaming \(x_2\) to \(x_1\)).

\[
\text{[S]: During which meeting did Mary kiss John?] = \\
\lambda P \lambda I[\text{which}(\lambda x_1[\text{MEETING}(x_1) \land \text{time}(x_1) \subseteq I], \\
\lambda y_0[a(\lambda x_0[\text{KISS(MARY, JOHN)}(x_0) \land \\
\text{time}(x_0) \subseteq \text{time}(y_0)), P)])].
\]

Expanding which and substituting \(T\) for \(P\) yields:

\[
\lambda I[?x[\text{MEETING}(x) \land \text{time}(x) \subseteq I \land \\
\exists x_0[\text{KISS(MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq \text{time}(x)]]).
\]

The resulting formula is exactly the same as that arising from direct construction. This is to be expected since the original interrogative sentence is unambiguous. The same is true for the two construction methods as ap-
The meaning of *afterwards* may be used in deriving the meaning of sentences such as (71). Of course, such sentences are more naturally interpreted as part of a multi-sentence discourse, rather than as stand-alone sentences. In a discourse, the toi of the sentence will be determined by the preceding sentences, which act as the context of the sentence.

(71) \([S, \text{Mary kissed John afterwards}] = \]
[\[\text{tPP afterwards}\] = \]
\[\lambda P \lambda I [\exists x_1 [\text{time}(x_1) \subseteq I, \lambda y_0 P(\text{time-from}(I, \text{time}(y_0)))]]]
\[= \lambda P \lambda I [\exists x_1 [\text{time}(x_1) \subseteq I, \lambda y_0 [\exists x_0 [\text{Kiss}(\text{Mary, John})(x_0) \wedge \text{time}(x_0) \subseteq \text{time-from}(I, \text{time}(y_0))]]]]
\]
Substituting once again \(\top\) for \(P\) and expanding the abbreviations \(a\), yields:

(72) \([S, \text{Mary kissed John afterwards}] = \]
\[\lambda I [\exists x_1 [\text{time}(x_1) \subseteq I] \wedge \exists y_0 [\exists x_0 [\text{Kiss}(\text{Mary, John})(x_0) \wedge \text{time}(x_0) \subseteq \text{time-from}(I, \text{time}(y_0))]]]]
\]
The resulting formula denotes that function of intervals, that given a toi \(I\), yields true if there is an event \(x_1\), the event-time of which is included within \(I\), and there is an event of Mary’s kissing John, the event time of which is included within \(I\), after the event time of \(x_1\).

### 4.6 Indirect construction

A second method of deriving the meaning representations of temporal questions corresponds to the indirect construction of quantified NPs in MG, via “quantifying-in”. This method is similar to the (single) construction method used for questions in (Karttunen, 1977), adapted for “when” questions in (Larson and Cooper, 1982). The latter paper is mainly concerned with the interaction of tense and ‘when’-questions. They show that the quantification introduced by tense should be allowed to have wider scope than the question. In this paper, we ignore tense.

In the original MG version of “quantifying-in”, first the meaning of a ‘gappy’ sentence with a pronoun is formed, and then the meaning of the quantified NP is applied to the meaning of the gappy sentence. In applying this method to the temporal domain, the particle *then* plays the part of the pronoun, used in forming a ‘gappy’ sentence. Then, the meaning of the tPP is applied to
balance between the referential and existential quantification view of \textit{then} as a temporal pronoun. In the literature on temporal anaphora, there is traditionally some tension between these two views of temporal dimension of sentences. See e.g. (Hinrichs, 1986; Kamp and Reyle, 1993; Partee, 1973). The free variable may be seen as referential, depending on a particular assignment, whereas the existential quantification on an event to be included within it may be seen as a concession to the quantificational view.

The final tPP meaning of \textit{then} is derived by applying the meaning of the null tP to the tNP meaning, as shown in (67).

\begin{equation}
\begin{align*}
\left[\text{tPP then}\right] &= \left[\text{tP}\right]\left[\lambda P \lambda I [a(\lambda x \{\text{time}(x) \subseteq I, P\})]\right] = \\
&= \lambda P \lambda I [P(\lambda y_0 [P(\text{time}(y_0))])(I)] \\
&= \lambda P \lambda I [a(\lambda x \{\text{time}(x) \subseteq I, P\})] = \\
&= \lambda P \lambda I [a(\lambda x_1 \{\text{time}(x_1) \subseteq I, \lambda y_0 [P(\text{time}(y_0))]\})].
\end{align*}
\end{equation}

The particle \textit{then} may be used to temporally modify sentences in the same way as other tPPs, by pseudo-applying its meaning to the meaning of the sentence:

\begin{equation}
\begin{align*}
\left[\text{S, Mary kissed John then}\right] &= \\
\left[\text{tPP then}\right]\left[\text{S, Mary kissed John}\right]_2 = \\
&= \lambda P \lambda I [a(\lambda x_1 \{\text{time}(x_1) \subseteq I, \lambda y_0 [P(\text{time}(y_0))]\})] \\
&= (2 \lambda P_0 \lambda I_0 [\lambda a(\lambda x_0 [\text{KISS(\text{MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq I_0, P_0)]])_2 = \\
&= \lambda P \lambda I [a(\lambda x_1 \{\text{time}(x_1) \subseteq I, \lambda y_0 [P(\text{time}(y_0))]\})].
\end{align*}
\end{equation}

By substituting $T$ for $P$ and expanding the abbreviations $a$, we get the following:

\begin{equation}
\begin{align*}
\left[\text{S, Mary kissed John then}\right] &= \\
&= \lambda I [\exists x_1 \{\text{time}(x_1) \subseteq I \land \\
&= \exists x_0 [\text{KISS(\text{MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq \text{time}(x_1)]]).
\end{align*}
\end{equation}

The resulting formula denotes that function, which given a toi $I$, yields $\text{true}$ if there is some event $x_1$, the event-time of which is included within $I$, such that there is an event $x_0$ of Mary’s kissing John, the event-time of which is included within the event time of $x_1$. Using similar construction methods, we may construct the tPP meanings of additional particles such as \textit{previously} and \textit{afterwards}.

\begin{equation}
\begin{align*}
\left[\text{tPP afterwards}\right] &= \left[\text{tP after}\right]\left[\text{tNP then}\right] = \\
&= \lambda P \lambda I [a(\lambda x_1 \{\text{time}(x_1) \subseteq I, \lambda y_0 [P(\text{time-from}(I, \text{time}(y_0))]))]].
\end{align*}
\end{equation}
4.5 The meaning of the particle then

The particle then plays an important role in the analysis of both indicative and interrogative temporally modified sentences. Its role in the temporal domain is analogous to the role played by pronouns in the NP domain. As well as being of independent interest, the use of this particle will be shown to provide an alternative construction method for both indicative and interrogative sentences. This alternative method is based on an analogy with MG’s rule of “Quantifying-in”. It is used in cases where it is necessary to assign an embedded quantifier wider scope than suggested by its sentential location.

The particle then may serve as a tPP as in (64). Its meaning is not considered in (Pratt and Francez, 1998), however we may assign it a meaning along the same lines as the meaning of when. In fact, as we shall see, when and then as well as additional particles all share the same core tN meaning as given in (49), repeated here as (65).

(64) Mary kissed John then.

(65) \( \lambda x \lambda I[\text{time}(x) \subseteq I] \).

Unlike in the meanings of regular tNs, the core meaning of then imposes no restriction on the event \( x \) other than having its event time included within the toi \( I \). The tNP meaning of then is derived by pseudo-applying the meaning of the determiner \( a \) to the core TN meaning.

(66) \[ \text{wh-Det}\overline{a}[1 \lambda x \lambda I[\text{time}(x) \subseteq I]]_1 = \\
\lambda Q \lambda P[a(Q, P)][(1 \lambda x \lambda I[\text{time}(x) \subseteq I])_1 = \\
\lambda P \lambda I[a(\lambda x[\text{time}(x) \subseteq I], P)] \]

The choice of existential quantification may seem somewhat un-intuitive here. A priori, one might expect the use of the definite determiner as part of the meaning of then. However, the framework of (Pratt and Francez, 1998), which we have been following, employs a Russellian interpretation of the definite determiner. Thus using the instead of \( a \) would impose a uniqueness constraint, allowing only a unique event (without any further restriction) within \( I \). This would erroneously rule out many possible values for \( I \), i.e. any interval containing more than one event. We therefore choose to employ existential quantification. Alternatively, one could switch to a more current interpretation of the definite determiner, yielding a more appropriate interpretation. Choosing existential quantification leads to an interesting
between the two representations is that the variable \( x_1 \) of type \( e \) is replaced by a variable \( J \) of type \( i \). In addition, the abstraction over \( y_0 \) in the second term of the operator \textbf{which} becomes unnecessary.

\[(60) \quad \lambda P \lambda I[\textbf{which}(\lambda J [J \subseteq I], P)].\]

Using this representation would lead to an alternative interpretation of \textbf{when} questions as in (61). This formula 'asks' about intervals and not about events.

\[(61) \quad \lambda I[?J [J \subseteq I \land \exists J_0[\text{KISS(MARY, JOHN)}(J_0) \land J_0 \subseteq J]]].\]

The alternative formulation using intervals instead of events means such extensions will include not only all those entities that may be referred to by calendrical items, but any interval included within the toi that includes an event of Mary's kissing John. This would seem to make the extension much larger, including any closed bounded interval which contains the event-time of Mary's kissing John. For this reason, we prefer to use the event formulation.

As discussed in Section 2, the extension of an interrogative formula is considered insufficient in the framework of G&S, requiring us to also compute its intension. The intension of \( ?x[\varphi(I, x)] \) is given in (62). The intension relative to a possible world \( w \) is the set of possible worlds in which the extension is the same as in \( w \). It is the set of possible worlds \( w' \) such that the set of meeting events during which Mary kissed John is the same as in \( w \).

\[(62) \quad \llbracket \omega x[\varphi(I, x)] \rrbracket_{M, w, \sigma} = \{ w' \mid w' \in W \land \llbracket \omega x[\varphi(I, x)] \rrbracket_{M, w', \sigma} = \llbracket \omega x[\varphi(I, x)] \rrbracket_{M, w, \sigma} \rrbracket.\]

Finally, we may compute the interpretation of the full formula as a function, which given an interval \( I \), yields the intension of \( ?x[\varphi(I, x)] \), i.e. a block of possible worlds. Writing the function as a set of pairs, the interpretation of the question may be given as (63), where \( D_1 \) is the time domain, i.e. the domain of intervals of the real line. Here we use the notation \( \psi[I'/I] \) to denote the formula \( \psi \) after substitution of \( I' \) for each free occurrence of \( I \). The intension is that function that for each temporal context interval \( I' \), yields the intension of the interrogative formula, relative to \( I' \).

\[(63) \quad \llbracket \lambda I[?x[\varphi(I, x)]] \rrbracket_{M, w, \sigma} = \{ (I', \llbracket \omega x[\varphi(I, x)] \rrbracket_{M, w, \sigma}) \mid I' \in D_1 \}.\]
4.4 The model-theoretic interpretation of question translations

We now turn to the formal model-theoretic interpretation of temporal questions. To simplify the presentation, we introduce the abbreviation \( \varphi(x, I) \) to denote the type \( t \) formula within the scope of the binding interrogative operator in (54).

\[
(57) \quad \varphi(I, x) = \text{def } \text{MEETING}(x) \land \text{time}(x) \subseteq I \land \\
\exists x_0 [\text{KISS(MARY, JOHN)}(x_0) \land \text{time}(x_0) \subseteq \text{time}(x)].
\]

Using this abbreviation, the meaning representation of the question may be written as (58).

\[
(58) \quad \lambda I[?x[\varphi(I, x)]].
\]

We now see how the interpretation of interrogatives described in Section 2 applies to such interrogative formulae. For simplicity, we start by computing the interpretation of the embedded interrogative formula within the scope of the lambda-abstraction over \( I \). Recall that the interpretation of interrogative formulae is computed in two steps, starting with the extension and moving on to the intension. The extension of \(?x[\varphi(I, x)]\) is given in (59). In a sense, it corresponds to the intuitive interpretation of the temporal question. For a given possible world \( w \), and some value assignment to the free variable \( I \), the extension is the set of meeting events such that their event-time is included in the value assigned to \( I \), and their event-time includes an event of Mary’s kissing John.

\[
(59) \quad [?x[\varphi(I, x)]]_{M, w, \sigma} = \{ \sigma'(x) \mid M, w, \sigma' = \varphi(I, x) \text{ and } \sigma \approx_x \sigma' \}.
\]

The extension of the corresponding \textit{when} question is the set of events of any kind, such that their event time includes an event of Mary’s kissing John within the toi. If \( x_0 \) and \( x_1 \) are two different events in the toi, such that \( x_0 \) is within the extension of a \textit{when} question, and the event time of \( x_1 \) includes that of \( x_0 \), then \( x_1 \) must also be in the extension. In particular, for calendrical entities, if a Monday is included in the extension of the question, then so is the week during which this Monday is contained, assuming that the toi is large enough. Similarly for the month, the year, etc. For this reason, it is convenient to interpret ‘when’ questions as asking about events rather than intervals. In (Pratt and Francez, 1997), a similar analysis to that of (Pratt and Francez, 1998) is presented, without explicitly using events, but rather their event times directly. Using this alternative formulation, we could represent the meaning of \textit{when} as (60) instead of (51). The difference
\[
\lambda P \lambda I [\text{which}(\lambda x_1 [\text{meeting}(x_1) \land \text{time}(x_1) \subseteq I_1], \lambda y_1 [P(\text{time}(y_1))])] \\
(2 \lambda P_0 \lambda I_0 [a(\lambda x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq I_0], P_0)]]_2 = \\
\lambda P \lambda I [\text{which}(\lambda x_1 [\text{meeting}(x_1) \land \text{time}(x_1) \subseteq I], \\
\lambda y_0 [a(\lambda x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0), P] )]].
\]

Expanding which and substituting \( T \) for \( P \) yields:

\[
(54) \lambda I [? x [\text{meeting}(x) \land \text{time}(x) \subseteq I \land \\
\exists x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq \text{time}(x)]]].
\]

The intuitive interpretation of this formula is the following. Given some toi \( I \), it asks for events \( x \), which are meetings and their event-time includes an event of Mary’s kissing John and is included in \( I \). The meaning of a when question may be derived in a similar fashion:

\[
(55) \text{[s, when did Mary kiss John] = } \\
[\text{[PP when] [s, Mary kissed John] } ]_2 = \\
\lambda P \lambda I [\text{which}(\lambda x_1 [\text{time}(x_1) \subseteq I_1], \lambda y_1 [P(\text{time}(y_1))])] \\
(2 \lambda P_0 \lambda I_0 [a(\lambda x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq I_0], P_0)]]_2 = \\
\lambda P \lambda I [\text{which}(\lambda x_1 [\text{time}(x_1) \subseteq I], \\
\lambda y_0 [a(\lambda x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq \text{time}(y_0), P] )]].
\]

By expanding which once more and substituting \( T \) for \( P \) we get the following meaning representation, which not surprisingly is similar to (54), without the the restriction on \( x \) being a meeting.

\[
(56) \lambda I [? x [\text{time}(x) \subseteq I \land \\
\exists x_0 [\text{kiss}(\text{mary, john})(x_0) \land \text{time}(x_0) \subseteq \text{time}(x)]]].
\]

The intuitive interpretation of the resulting formula is a function which given an interval \( I \), ‘asks’ for events \( x \) such that their event-time is included in \( I \), and there is a kissing event included within their event-time. According to this interpretation, when-questions ‘ask’ about events and not times. This may appear to be un-intuitive. However, in the framework of (Pratt and Francez, 1998), the notion of event is understood quite broadly. For example, as shown above, calendrical items e.g. Monday are interpreted as referring to events, not times. If calendrical items are interpreted as referring to events, it is natural to interpret when questions as ‘asking’ about events, in this broad sense, as well. We will return to this point after we present the model-theoretic interpretation of temporal questions.
\[ \lambda P \lambda I[ \textbf{which}(\lambda x_1 [\text{meeting}(x_1) \land \text{time}(x_1) \subseteq I],)
\]
\[ \lambda y_0 [P(\text{time}(y_0))]]. \]

(48) \[ [\text{PP after which meeting}] = [\text{PP after}][\text{INP the meeting}] = \]
\[ \lambda P \lambda I[ \textbf{which}(\lambda x_1 [\text{meeting}(x_1) \land \text{time}(x_1) \subseteq I],)
\]
\[ \lambda y_0 [P(\text{time-from}(I, \text{time}(y_0)))]]. \]

The meaning of the wh-word \textbf{when} may be constructed in a similar manner, starting from a TN meaning, adding the determiner \textbf{which} and finally the null tP \emptyset. As the TN we take the function in (49). This function is similar to the meaning of a TN such as \textbf{meeting} with the restriction on the event argument \( x \) being a meeting (or anything else) dropped. The only restriction left is the inclusion of the event-time of \( x \) within the toi, \( I \).

(49) \[ \lambda x \lambda I[\text{time}(x) \subseteq I]. \]

Pseudo-applying the meaning of the determiner \textbf{which} to this function yields (50). Applying the meaning of the null tP to the result yields the final meaning of \textbf{when}, as shown in (51).

(50) \[ [\text{wh-Det which}]_1 = [\lambda \lambda P \lambda I[ \textbf{which}(Q, P)](\lambda x \lambda I[\text{time}(x) \subseteq I])]_1 = \]
\[ \lambda P \lambda I[ \textbf{which}(\lambda x[\text{time}(x) \subseteq I], P)] \]

(51) \[ [\text{wh-tPP when}]_2 = [\text{PP \emptyset}][\lambda P \lambda I[ \textbf{which}(\lambda x[\text{time}(x) \subseteq I], P)] = \]
\[ \lambda P \lambda P \lambda I[\lambda y_0[P(\text{time-from}(I, \text{time}(y_0)))](I)] \]
\[ (\lambda P \lambda I[ \textbf{which}(\lambda x[\text{time}(x) \subseteq I], P)]) = \]
\[ \lambda P \lambda I[ \textbf{which}(\lambda x_1 [\text{time}(x_1) \subseteq I], \lambda y_0 [P(\text{time}(y_0))])]. \]

We may now use the meanings of interrogative tPPs to construct the meanings of interrogative sentences, starting with the direct construction method.

4.3 Direct construction

The direct construction method proceeds by using the meaning of an interrogative tPP in the same way as indicative tPPs, by directly pseudo-applying its meaning to the meaning of a sentence. For example, for (52), we pseudo-apply the meaning of the interrogative tPP to that of the sentence, as shown in (53).

(52) \textbf{During which meeting did Mary kiss John?}

(53) \[ [S, ? \text{During which meeting did Mary kiss John?}] = \]
\[ [\text{PP during which meeting}]_2 [S, \text{Mary kissed John}]_2 = \]
In Section 2, this function accepts two arguments and partitions the set of possible worlds into blocks (or equivalence classes) according to the values of \( x \) that satisfy both \( P \) and \( Q \) in each possible world. The meaning of \textit{which} has a different type than that of other determiners.\(^\text{7}\) Since the embedded interrogative formula in (44), \( ?x[P(x)\land Q(x)] \) has type \((s,t)\), the full formula has type \(((e,t),((e,t),(s,t)))\), unlike other determiners which have type \(((e,t),(e,t),t))\).

We may now construct the meaning of an interrogative \textit{tNP} with the by now familiar method of pseudo-applying the meaning of the determiner to the meaning of the \textit{tN} as shown in (45).

\[
(45) \quad [\text{wh-tNP which meeting}] = [\text{wh-Det which}[1[\text{IN meeting}]]] = \\
\lambda Q\lambda P[\text{which}(Q,P)](1\lambda x\lambda I[\text{MEETING}(x)\land \text{time}(x) \subseteq I])1 = \\
\lambda P\lambda I[\text{which}(\lambda x[\text{MEETING}(x)\land \text{time}(x) \subseteq I] , P)] = \\
\lambda P\lambda I[\lambda x[ \text{MEETING}(x)\land \text{time}(x) \subseteq I\land P(x)]].
\]

The meaning of this interrogative \textit{tNP} is a function of a predicate \( P \) and temporal context interval \( I \), which 'asks' for a specification of the meeting events \( x \), the event-time of which is included within \( I \), and that satisfy \( P \). More precisely, this meaning is a function, which given \( P \) and \( I \), partitions the set of possible worlds according to the possible values of \( x \) that satisfy three conditions: they are meetings, their event-time is included within \( I \), and they satisfy \( P \). This \textit{tNP} has a different type than indicative \textit{tNPs}. Its type is \(((e,t),(i,s,t))\), in contrast with indicative \textit{tPPs}, which have type \(((e,t),(i,t))\). Combining the interrogative determiner \textit{which} with a singular \textit{N} is frequently assumed to impose a presupposition of uniqueness with respect to the possible answers. We follow several authors (e.g., (Engdahl, 1986)) in seeing this issue as pragmatic, and thus exclude it from the representation.

The meaning of the interrogative \textit{tPP during which meeting} may now be derived by applying the meaning of the \textit{tP during}, repeated in (46), to the meaning of \textit{which meeting}. However, the difference in types between indicative and interrogative \textit{tNPs} leads us to a polymorphic view of the meanings of \textit{tPs}. In particular, the variable \( \mathcal{P} \) for which we substitute the meaning of the \textit{tNP} has to be of the same type as of the \textit{tNP} to which the \textit{tP} is applied.

\[
(46) \quad [\text{tP during}] = \lambda \mathcal{P}\lambda P\lambda \mathcal{I}[\mathcal{P}(\lambda y[P(y)])](I].
\]

The meaning of interrogative \textit{tPPs} is given as follows:

\[
(47) \quad [\text{wh-tPP during which meeting}] = \\
[\text{tP during}][[\text{wh-tNP which meeting}]] = 
\]
4.1 The meaning of yes/no questions

The meaning of yes/no questions such as (40) depends on the temporal context in much the same way as does the meaning of indicative sentences. A question may receive different answers depending on the toi with respect to which it is evaluated.

(40) Did Mary kiss John?

The ILQ translation of this question is constructed by pseudo-applying the meaning of the auxiliary did to the meaning of the corresponding indicative sentence. The meaning of the auxiliary is represented by (41). In this representation $\mathcal{P}$ is a type $(\epsilon,\eta,\iota)$ variable.

(41) $[\text{aux Did}] = \lambda P \lambda P[?(P(P))]$.

The meaning of (40) is derived by pseudo-applying (41) to the meaning of the indicative sentence, as follows:

(42) $[\text{S},? \text{Did Mary kiss John?}] = [\text{aux Did}]([\text{S, Mary kiss John}])1 = 
\lambda P \lambda P[?(P(P))] 
(1 \lambda P0 \lambda P1[\lambda \epsilon x0[\text{KISS(MARY, JOHN)}(x0) \land \text{time}(x0) \subseteq I], P0])1 = 
\lambda P \lambda P[?(\lambda \epsilon x0[\text{KISS(MARY, JOHN)}(x0) \land \text{time}(x0) \subseteq I], P)].$

After instantiating $\top$ for $P$, and expanding $\lambda P$, we get:

(43) $\lambda I[? \exists x0[\text{KISS(MARY, JOHN)}(x0) \land \text{time}(x0) \subseteq I]].$

The resulting formula is dependent on the toi $I$.

4.2 The meaning of interrogative tPPs

We may construct the meanings of interrogative tPPs using the same method used for indicative tPPs. Starting with the tN, e.g. meeting, adding the determiner which and finally the tP during. The meaning of which is shown in (44).

(44) $[\text{wh-DETwhich}] = \lambda Q \lambda P[\text{which}(Q, P)] = \text{def} \lambda Q \lambda P[? x[Q(x) \land P(x)]]$.

The meaning of this determiner has the same form as that of the more familiar determiners, such as $a/the/every$. Intuitively, this meaning is a function that given two type $(\epsilon,\iota)$ arguments $P$ and $Q$, “asks” for those values of $x$ which satisfy both $P$ and $Q$. More formally, employing the interpretation of
The other role of sentences, the role of complements of tPPs is realized by combining the meaning of a tP with the meaning of a sentence. Since sentence meanings are tGQs, this is achieved in the same manner as for tPPs formed from tNPs, by applying the meaning of the tP to that of the sentence as in (39). The result is a tPP which may be further used to temporally modify sentences.

\[
\text{\text{\small (39) } [tPP_{after\ Mary\ kissed\ John}] = [tPP_{after}[tS_{\text{Mary\ kissed\ John}}]] = } \\
\lambda P \lambda I [\text{the(}\lambda x_1 [\text{KISS(MARY, JOHN)(x_1)] \land \text{time(x_1)} \subseteq I}], \\
\lambda y_0 [P(\text{time-from}(I, \text{time(y_0))))]].
\]

4 The meaning of temporal questions

In this section we provide a principled account of temporal questions in ILQ. Our analysis is divided into two stages. First, we give a compositional method for translating NL temporal questions into ILQ, which is an extension of the analysis of temporal sentences. This method is based on the translation procedure defined for general questions in (Nelken and Francez, 1998). We start by considering yes/no questions, and then turn to constituent questions. For the latter, we present two alternative construction methods, referred to as direct and indirect construction, based on the corresponding construction methods for sentences containing quantified NPs in MG. The place of pronouns in the indirect construction method, will be taken over by the particle then, which serves as a temporal pronoun. Our analysis emphasizes the role of expressions such as during which meeting, which we refer to as interrogative tPPs, reserving the name indicative tPPs for the kind of tPPs discussed above. We use the same nomenclature also at the level of tNPs, distinguishing indicative tNPs formed by use of the determiners described above and interrogative tNPs formed by use of the determiner which. Then, we consider the model-theoretic interpretation of question translations according to the interpretation of questions described in Section 2.
(34) \[ [S, \text{Mary kissed John}] = \\
\lambda I[a(\lambda x_0[\text{kiss(Mary, John)}(x_0) \& \text{time}(x_0) \subseteq I], \top)]. \]

Writing the meaning of sentences in this way, it becomes apparent that by replacing \( \top \) with a lambda-abstracted variable \( P \), and replacing the determiner \( a \) with a schematic quantifier \( Q \), we get a meaning representation of the form of tGQs, bearing striking resemblance to the meanings of tNPs, as in (35). We use the symbol \( S_1 \) for this form of meaning. The original meaning representation in (34) is recoverable from (35) by instantiating \( P \) to \( \top \) and \( Q \) to \( a \). Instantiation by other values for these variables may be used for the meanings of subordinate clauses. For simplicity, we will not consider such cases here.

\[
(35) [S, \text{Mary kissed John}] = \\
\lambda P \lambda I[Q(\lambda x_0[\text{kiss(Mary, John)}(x_0) \& \text{time}(x_0) \subseteq I], P)].
\]

Given these meaning representations, we may now see the double role of sentences. First, consider temporal modification. We employ the simplifying assumption that temporal modification occurs at the sentential level, and not at the more plausible VP level. Temporal modification of sentences proceeds by combining the meaning of a tNP with that of the sentence, using a second variant of pseudo-application, denoted \((\sigma \ldots)\), and defined as follows:

\[
(36) \lambda Q \lambda u[\psi(Q, u)](\lambda v(\varphi(P, v))_2 = \text{def} \\
\lambda P \lambda u[\lambda v[\varphi(P, v)](\lambda v(\varphi(P, v))_2 = \\
\lambda P \lambda u[\psi(\lambda v[\varphi(P, v)], u)].
\]

Pseudo-applying the meaning of the tPP to the \((S_1)\) meaning of the sentence yields the meaning of the temporally modified sentence (37).

\[
(37) [S, \text{Mary kissed John during the meeting}] = \\
[S, \text{Mary kissed John}]_2 = \\
\lambda P \lambda I[\text{the}(\lambda x_1[\text{meeting}(x_1) \& \text{time}(x_1) \subseteq I], \lambda y_1[\text{time}(y_1))]_2 \\
(\lambda P_0 \lambda I_0[a(\lambda x_0[\text{kiss(Mary, John)}}(x_0) \& \text{time}(x_0) \subseteq I_0], P_0)]_2 = \\
\lambda P \lambda I[\text{the}(\lambda x_1[\text{meeting}(x_1) \& \text{time}(x_1) \subseteq I], \\
\lambda y_0[\lambda x_0[\text{kiss(Mary, John)}}(x_0) \& \text{time}(x_0) \subseteq \text{time}(y_0), P)]_2.
\]

Notice that a temporally modified sentence is once more a tGQ. Herein lies the great power of the system. It allows multiple tPPs to temporally modify sentences by step-by-step application of temporal modification. For example:

\[
(38) [S, \text{Mary kissed John during every meeting one Monday}] = \\
\lambda P \lambda I[a(\lambda x_0[\text{kiss(Mary, John)}}(x_0) \& \text{time}(x_0) \subseteq \text{time}(y_0), P)]_2.
\]
Whereas during locates events within the intervals denoted by their complement, a tP such as after locates events within the toi subsequently to the interval picked out by their complement. This is achieved by defining Temporal warp functions. For after, a partial function denoted ‘time-from’ is defined as in (28). Intuitively, this function nudges an interval forwards. The meaning of after is given in (29).

(28) \( \text{time-from}([a, b], [c, d]) = \text{def} [d, b] \) if \([c, d] \subseteq [a, b] \).

(29) \([\text{tP after}] = \lambda P \lambda \lambda I[P(\lambda y_0[P(\lambda (\text{time}(y_0)))])(I)] \).

Applying the meaning of after to a tNP such as the meeting yields:

(30) \([\text{tP after the meeting}] = [\text{tP after}][\text{tNP the meeting}] = \lambda P \lambda I[\text{the}(\lambda x_1[\text{MEETING}(x_1) \wedge \text{time}(x_1) \subseteq I] \lambda y_0[P(\text{time-from}(I, \text{time}(y_0)))])(I)] .

Another meaning of after is just after. This meaning is captured by replacing the warp function ‘time-from’ in the meaning of after with the function ‘just-after’, defined in (31), where \( \varepsilon \) is a contextually determined parameter.

(31) \( \text{just-after}([a, b], [c, d]) = \text{def} [d, d + \varepsilon] \) if \([c, d] \subseteq [a, b] \).

3.3 The meaning of sentences

The meanings assigned to sentences in (Pratt and Francez, 1998) is based on the double role that they may play, either being modified by tPPs as in (32), or serving as complements of tPPs as in (33), as do tNPs.

(32) Mary kissed John during the meeting.

(33) Bill kissed Sue after Mary kissed John.

As we saw above, sentences without temporal modification introduce an existentially quantified event argument \( x_0 \) and a lambda-abstracted context-dependent variable \( I \). However, in order to accentuate the symmetry of meanings with tNPs, the meaning representation of sentences is changed slightly. First, we replace the existential quantification over \( x \) by the determiner \( a \), as in (34). Here \( T \) is an abbreviation for \( \lambda x[\text{TRUE}] \), a predicate true of every individual entity \( x \).
The meanings of tNPs are viewed as *temporal generalized quantifiers* (tGQs), which are temporal analogs of GQs. However, we cannot directly apply the meaning of one of the determiners above to the meaning of a tN, since the type of the determiners is incompatible with the type of tNs. This problem is overcome by employing a non-standard semantical operation called pseudo-application, denoted by \((1\ldots)\) and defined in (23). As hinted by the subscript, a second variant of pseudo-application, denoted by \((2\ldots)\) will be defined below.

\[
(23) \lambda Q \lambda P [\psi(Q, P)](1\lambda x \lambda v [\varphi(x, v)])_1 = \text{def} \\
\lambda P \lambda v [\psi(Q, P)](\lambda x [\varphi(x, v)]) = \\
\lambda P \lambda v [\psi(\lambda x [\varphi(x, v)], P)].
\]

Pseudo-applying the meaning of a determiner to the meaning of a tN yields a tGQ. For instance, pseudo-applying the meaning of the determiner \(a\) to that of the tN *meeting* yields the meaning of *a meeting* as in (24).

\[
(24) \begin{align*}
\text{tNP}_a \text{meeting} = & \text{Det}_a \text{meeting} \mid \text{tNP}_{\text{meeting}} \\
= & \lambda P \lambda I [\alpha(\lambda x [\text{MEETING}(x) \land \text{time}(x) \subseteq I], P)].
\end{align*}
\]

Quantified calendrical tNs such as *one Monday* are assigned meanings in the same way. Non-quantified calendrical tNs are interpreted as tNPs by applying an implicit determiner. For example, *Monday*, taken as a tNP, is understood as having an implicit definite determiner *the*, meaning something like: *the unique Monday within the toi*.

### 3.2 Temporal preposition phrases

The meanings of tPPs are constructed in (Pratt and Francez, 1998) by applying the meaning of the head temporal proposition (tP) to the complement tNP. The meaning of the tP *during* is given in (26), where \(\mathcal{P}\) is a variable of type \((i.e.t.t)\). The intuitive meaning of *during* denotes some kind of inclusion or containment. This is not part of the meaning of *during* as given in (26), but rather arises due to the application of the tPP to the modified sentence as described below. The meaning of *during* is also shared by several other tPs, such as *on*. A similar meaning is attributed to a null temporal proposition denoted \(\emptyset\). Such a tP is proposed for tPPs such as *one Monday* as in:

\[
(25) \text{Mary kissed John [tPP}\emptyset {\text{one Monday}}].
\]

\[
(26) \begin{align*}
\text{tP}_{\text{during}} = & \lambda \mathcal{P} \lambda P \lambda I [\mathcal{P}(\lambda y_0[\text{P}(y_0)])](I) \\
= & \lambda \mathcal{P} \lambda I [\lambda x [\text{TIME}(x) \subseteq I], P].
\end{align*}
\]
how they modify sentences.

(14) Mary kissed John during the meeting.
(15) Mary kissed John during the meeting on a Monday.

3.1 The meaning of temporal noun phrases

A basic distinction is drawn in (Pratt and Francez, 1998) between non-temporal nouns such as book or tree, which do not have a temporal dimension and temporal nouns (tNs) such as Monday or meeting, which do. The former are interpreted as functions accepting an argument \(x\) of type \(e\), according to the standard MG treatment, as in (16). The latter have two arguments, a type \(e\) argument \(x\), representing an event, and a temporal context argument \(I\), called the time of interest (toi), as shown in (17). The determination of the value of the toi depends on several factors. It is driven by discourse, and constrained by tense. These factors are not incorporated in the account of (Pratt and Francez, 1997; Pratt and Francez, 1998), and are ignored here as well. A variable \(x\) satisfies the predicate meeting just in case \(x\) is assigned the value of a meeting event. The function “time” maps an event to its temporal trace, called its event-time. In the meaning of a tNP, the event-time is required to be included within the toi. Calendrical tNs such as Monday are interpreted in a similar manner, as shown in (18).

(16) \([_N\text{book}] = \lambda x[\text{book}(x)]\]
(17) \([_N\text{meeting}] = \lambda x\lambda I[\text{meeting}(x) \land \text{time}(x) \subseteq I]\]
(18) \([_N\text{Monday}] = \lambda x\lambda I[\text{Monday}(x) \land \text{time}(x) \subseteq I].\]

Non-temporal noun phrases (NPs) have their usual generalized quantifier (GQ) meanings as in MG, constructed by applying the meaning of a determiner to the meaning of a noun. The meanings of determiners are given in the familiar way, by:

(19) \([_\text{Det a}] = \lambda Q\lambda P[\exists x(Q(x) \land P(x))],\]
(20) \([_\text{Det every}] = \lambda Q\lambda P[\forall x(Q(x) \rightarrow P(x))]\],
(21) \([_\text{Det no}] = \lambda Q\lambda P[\neg \exists x(Q(x) \land P(x))],\]
(22) \([_\text{Det the}] = \lambda Q\lambda P[\exists ! x(Q(x)) \land \exists ! x(Q(x) \land P(x))].\]
The extension relative to a structure $M$, world $w$ and assignment function $\sigma$ is the set of individuals $d$ in the domain, that are such that $\text{kiss}(d, \text{John})$ holds in $M, w$. The intension is the set of possible worlds $w'$, such that the extension of the formula is the same in $w$ and $w'$, i.e. the set of possible worlds $w'$ in which the same people kissed John as in $w$. It thus partitions $\mathcal{W}$ into equivalence classes, according to who kissed John in those worlds. These equivalence classes are the sets of possible worlds in which nobody kissed John, those in which only Mary kissed John, those in which only Mary and Sue kissed John etc.

Speaking informally and anthropomorphically, we will sometimes say that a binary choice interrogative formula $\exists[\varphi]$ asks for the truth value of the indicative formula $\varphi$. Similarly, a constituent interrogative formula $\exists[x][\varphi]$ is said to ask for the values that may be assigned to the tuple of variables $x$ in order to render $\varphi$ true.

3 The semantics of temporal preposition phrases

In this section we present the semantics of temporal preposition phrases, based on (Pratt and Francez, 1998). This framework provides an analysis of the semantics of sentences modified by tPPs. The treatment of such sentences is based on the use of two temporally-related arguments, denoting an event and a contextually determined interval. For example, an assertive event-reporting sentence such as (12) is assumed to contribute an existentially quantified event argument, denoted by $x_0$, and a lambda-abstracted context variable $I$, with the restriction that the time-span of $x_0$ be included within $I$. Thus the meaning of this sentence may be represented as in (13).

(12) Mary kissed John.

(13) $\lambda I[3x_0([\text{Mary}, \text{John}](x_0) \wedge \text{time}(x_0) \subseteq I)].$

These two temporal arguments play an important role in the treatment not only of sentences but also of temporal noun-phrases, thus providing a basis for the analysis of temporally modified sentences such as (14). This analysis provides a treatment of cascaded tPP modification by temporally quantified tPPs as in (15). We now briefly present the main ideas of (Pratt and Francez, 1998), building up from the meanings of tNPs, to the meanings of tPPs and
The motivation behind this definition is the following. In a structure, the set of possible worlds \( \mathcal{W} \) represents a set of alternative epistemic possibilities. A hypothetical agent, having only partial knowledge of the state of affairs in the real world may entertain several different alternatives, each represented as a possible world. An interrogative formula partitions \( \mathcal{W} \) into equivalence classes, blocks of possible worlds. Two possible worlds are equivalent (belong to the same block) iff the extension of the interrogative formula is the same in both, i.e. if the question is answered in the same way in both.

To illustrate this interpretation, consider the following NL questions and their ILQ representations. For a compositional derivation of these ILQ formulae, see (Nelken and Francez, 1998). In general, if \( \mathbf{E} \) is an NL-expression of syntactic category \( \mathbf{C} \), we use \( [\mathbf{C}, \mathbf{E}] \) to denote the ILQ meaning representation of \( \mathbf{E} \).

First, consider a yes/no question such as (5), represented in ILQ as (6). The extension and intension of this formula are given in (7) and (8).

\[
(5) \text{ Did Mary kiss John?} \\
(6) \text{ [S: Did Mary kiss John?] = } [\text{kiss(Mary, John)}] \\
(7) [\text{S: } \text{kiss(Mary, John)}]_{M, w, \sigma} = \llbracket \text{S: kiss(Mary, John)} \rrbracket_{M, w} \\
(8) [\text{S: } \text{kiss(Mary, John)}]_{M, w, \sigma} = \\
\{ w' \in \mathcal{W} | \llbracket \text{S: } \text{kiss(Mary, John)} \rrbracket_{M, w', \sigma} = \llbracket \text{S: kiss(Mary, John)} \rrbracket_{M, w, \sigma} \}.
\]

The extension is the truth value of the corresponding indicative formula. The intension in a world \( w \) is the set of possible worlds \( w' \) in which the formula \( \text{kiss(Mary, John)} \) has the same truth value as in \( w \). Interrogative binary choice formulae divide \( \mathcal{W} \) into two equivalence classes, one in which the truth value of the corresponding indicative formula is true, and one in which it is false. As an example of a constituent question, consider (9). Its extension and intension are presented in (10) and (11).

\[
(9) \text{ [S: Who kissed John?] = } [\text{kiss(John)}] \\
(10) [\text{S: } \text{kiss(John)}]_{M, w, \sigma} = \{ \sigma' | \sigma' \approx \sigma \text{ and } M, w, \sigma' \models \text{kiss(John)} \}. \\
(11) [\text{S: } \text{kiss(John)}]_{M, w, \sigma} = \\
\{ w' \in \mathcal{W} | \llbracket \text{S: } \text{kiss(John)} \rrbracket_{M, w', \sigma} = \llbracket \text{S: kiss(John)} \rrbracket_{M, w, \sigma} \}.
\]
a non-empty set of possible worlds, all mutually accessible, $V$ is a function, which for any possible world $w$ yields a valuation of type $t$ formulae into \{$false, true\}$ and $I$ is an interpretation function. The domain is common to all possible worlds. The interpretation of indicative ILQ formulae is the usual IL interpretation. In a given structure and possible world the extension of an indicative formula $\psi$ of type $t$, written $[e\psi]_{M,w,\sigma}$ is a truth value. Its intension in a structure $M$, written $[i\psi]_{M,\sigma}$ is the subset of possible worlds in which its extension is the truth value $true$. For interrogative formulae, the picture is more complex. G&$S$ claim that we cannot interpret interrogatives extensionally. Even in a fixed possible world, we have to look at their intensions. The intension of an interrogative formula $\varphi$, written $[i\varphi]_{M,w,\sigma}$ is computed in two stages, by going through its extension, $[e\varphi]_{M,w,\sigma}$.

The extension of a binary choice interrogative formula $?\varphi$ is just the truth value of $\varphi$. The extension of a constituent interrogative formula of the form $?x\varphi$ is the set of possible domain element tuples, to which $x$ may be assigned, as given in Definition 2. We use the notation $\sigma \approx_x \sigma$ to signify that assignments $\sigma, \sigma'$ differ at most with respect to the value they assign to the variable $x$. Similarly, we write $\sigma' \approx_\bar{\sigma} \sigma$ to signify that assignments $\sigma, \sigma'$ differ at most with respect to the values they assign to the variable tuple $\bar{\sigma}$.

**Definition 2 (ILQ Extensional interpretation)** Let $\varphi \in IL$ be of type $t$.

1. $[e?\varphi]_{M,w,\sigma} = [e\varphi]_{M,w,\sigma} = \begin{cases} true & \text{if } M, w, \sigma \models \varphi \\ false & \text{otherwise} \end{cases}$

2. $[e?x\varphi]_{M,w,\sigma} = \{ \langle \sigma'(x_1), \sigma'(x_2), \ldots, \sigma'(x_n) \rangle \mid \sigma' \approx_\bar{\sigma} \sigma \text{ and } M, w, \sigma' \models \varphi \}$.

The intension of an ILQ interrogative formula in a given possible world, $w$, is the set of possible worlds in which the extension of the formula is the same as in $w$. It is thus a type $(s,t)$ entity.

**Definition 3 (ILQ Intensional interpretation)** Let $\varphi \in IL$ be of type $t$. 


ILQ enhances IL by the addition of two new operators defined on type $t$ formulae: the *interrogative operator* `?`, used to represent the meanings of yes/no questions and the *binding interrogative operator* `?x`. We call type $t$ IL formulae *indicative formulae*. If $\phi$ is an indicative formula, then a formula of the form `?[\phi]` is called a *binary choice interrogative formula*. A formula of the form `?x_1?x_2\ldots?x_n[\phi]` is called a *constituent interrogative formula*, and is used to represent the meaning of a constituent question. We will sometimes use the notation $\phi'$ to denote an arbitrary indicative formula and $\phi?$ to denote an arbitrary interrogative formula (either binary choice or constituent). This is not part of the formal syntax of ILQ, but a convenient notational device.  

Other than the addition of these two new operators, ILQ shares IL’s vocabulary, including IL’s connectives, quantifiers and operators, and for each type $a$, an infinite set of constants $CON_a$ and variables $VAR_a$. We use the following variable names, possibly with numeric subscripts: $x, y$ are variables of unspecified type, $u, v$ are variables of type $e$, $P, Q$ are of type $(e, t)$. In addition, ILQ contains the symbol for identity (as does IL).

**Definition 1 (ILQ Syntax)** The set $W_{ILQ}$ of ILQ formulae is the smallest set of formulae satisfying the following conditions:

1. If $\phi$ is an IL formula, then $\phi \in ILQ$ and is of the same type as in IL.
2. If $\phi \in ILQ$ is of type $t$, then $?[\phi] \in ILQ$ and is of type $(s, t)$.
3. If $\phi \in ILQ$ is of type $t$, and $x_1, x_2, \ldots, x_n$ are variables of any types, then $?[x_1, x_2, \ldots, x_n[\phi] \in ILQ$ and is of type $(s, t)$.
   For $\bar{x} = (x_1, x_2, \ldots, x_n)$, we use the abbreviation $?\bar{x}[\phi]$.
4. If $\phi \in ILQ$ is of type $b$, and $x$ is a variable of type $a$, then $\lambda x[\phi] \in ILQ$ and is of type $(a, b)$.
5. If $\phi \in ILQ$ is of type $(a, b)$ and $\psi$ is of type $a$, then $\phi(\psi) \in ILQ$ and is of type $b$.

Structures for ILQ are the same as structures used for IL in MG. A structure is a tuple $(D, W, V, I)$ where $D$ is a non-empty set, its domain (from which non-empty interpretation domains for each type may be constructed), $W$ is
also applicable in the temporal domain, we chose to adopt a more familiar framework here, namely that of G&S.

The second stage of the analysis is the interpretation of ILQ meaning representations in model-theoretic terms according to the framework of G&S. In this paper, we discuss extensional, direct questions in a static setting, focusing on event-reporting sentences, as we believe these form the ground-level components of any semantic theory of questions. We discuss examples such as the following:

1. When did Mary kiss John?
2. When did Mary kiss John during every meeting?
3. When did Mary kiss John during one summer?
4. When did Mary kiss John after they met?

The framework presented here may be enhanced to deal with addition phenomena, which fall outside these boundaries.

The paper is structured as follows. In Section 2, we present ILQ. In Section 3 we review the meanings of temporal preposition phrases according to (Pratt and Francez, 1998). In Section 4 we provide a method for deriving the meanings of temporal questions in ILQ and discuss the model-theoretic interpretation of these translations. In Section 5, we consider some semantic notions related to the meanings of questions including answerhood and entailment.

2 ILQ

We begin by introducing ILQ, a language for representing the meanings of both indicative and interrogative temporal sentences. ILQ is based on an extensional fragment of IL, and is closely related to the language used by G&S. ILQ shares the basic types of IL, with the addition of a type \( i \) of temporal intervals, interpreted as closed bounded intervals of the real line. For detailed justification of this type see (Pratt and Francez, 1997). We use the variable \( I \), possibly with numeric subscripts, as a variable ranging over type \( i \) elements. The construction of compound (functional) types from the basic ones proceeds as in IL.
The semantic handling of temporal questions requires the integration of theories for the semantics of interrogatives and temporal expressions. For a recent survey of the semantics of questions see (Groenendijk and Stokhof, 1997). It is generally accepted that the semantics of questions should provide answerability conditions for them in direct analogy with truth conditions for indicative sentences. Just as truth conditions determine when an indicative sentence is true, so do answerability conditions determine when an interrogative sentence is answerable. There is less agreement on how answerability conditions should be formally defined. In this paper, we adopt the framework of Groenendijk and Stokhof (henceforth G&S) (Groenendijk and Stokhof, 1982; Groenendijk and Stokhof, 1984; Groenendijk and Stokhof, 1993; Groenendijk and Stokhof, 1997). The meaning of a question according to this interpretation is a partition of the set of epistemic possibilities into equivalence classes, according to the possible answers to the question. Our main motivation in choosing this framework is that it introduces some interesting semantic notions such as interrogative entailment and answerhood, allowing us to examine these notions with respect to temporal interrogatives. The temporal component of our analysis is based on the treatment of temporal preposition phrases (tPPs) of (Pratt and Francez, 1998). This analysis introduces Temporal Generalized Quantifiers (tGQs) as temporal analogs of the well-known generalized quantifiers (Barwise and Cooper, 1981). Temporal generalized quantifiers have a double role, serving as meanings of both temporal NPs (tNPs) and sentences.

In this paper we integrate the two fields by presenting a novel account of the semantics of temporal questions in a Montague Grammar (MG) style framework (Gamut, 1991; Montague, 1973). Our account is based on a two-stage interpretation. Temporal questions are first compositionally translated into a formal meaning representation language, called Intensional Logic with Questions (ILQ), an extension of Montague’s IL. This language is related to, but more expressive than the one used by (Groenendijk and Stokhof, 1997). ILQ extends IL by introducing interrogative formulae in addition to regular IL formulae. Actually, we will define only an extensional language, since we do not consider intensional phenomena in this paper. The translation procedure of temporal questions into ILQ, is based on (Nelken and Francez, 1998) and is simpler and more straightforward than previous accounts. In (Nelken and Francez, 1998), this construction method is complemented by a novel interpretation of questions, based on a non-standard interpretation of the type t, modeled by bilattices (Fitting, 1991; Ginsberg, 1988; Ginsberg, 1990). While the results of (Nelken and Francez, 1998) are
The Semantics of Temporal Questions

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Abstract

In this paper, we provide a characterization of the semantic interpretation of temporal questions. This analysis is based on the framework of (Pratt and Francez, 1998) for the semantics of the temporal element of sentences and that of (Groenendijk and Stokhof, 1984) for the semantics of questions. We present a method of compositionally constructing the meanings of questions based on the introduction of interrogative temporal preposition phrases and two construction methods corresponding to the direct and indirect construction methods for quantified NPs in Montague Grammar. We give an interpretation of the resulting constructions according to the principles of (Groenendijk and Stokhof, 1984).

1 Introduction

In the study of the formal semantics of natural language (NL), considerable attention has been paid to both the subjects of temporal expressions and interrogative sentences. However, little work has been done on their interaction. In this paper we address the issue of temporal interrogative sentences (henceforth temporal questions), which may be defined as questions that ask about the temporal location of an event or state mentioned in the sentence.