In dialogue with a desktop calculator:
A concurrent stream processing approach
to building simple conversational agents

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Abstract

Human spontaneous face-to-face conversations are characterized by phenomena such as turn-taking, feedback, sounds of hesitation and repairs. A simple and highly modular stream-based approach to natural language processing is proposed that attempts to deal with such things. A basic version of the model has been implemented in the Oz programming language.

1. Introduction

"And you do Addition?" the White Queen asked.
"What's one and one and one and one and one and one and one and one and one and one and one?"
"I don't know," said Alice. "I lost count."
"She can't do Addition," the Red Queen interrupted.

Lewis Carroll: “Through the Looking Glass”

Suppose we would like to hook up a desktop or pocket calculator to speech recognition and speech synthesis hardware and software, so as to enable people to solve arithmetic problems in an interactive fashion, in spoken dialogue with the resulting system. Imagine for example being able to ask something like [tuː pləs thrɪː:] and after a short pause receive the answer [fæɪv]...
Finally, note the long stretch of silence between the second and third turn. It illustrates the fact that, depending on the state of the dialogue, a pause – long or short – may sometimes not mean anything at all.

### 2.2. Sounds of hesitation

The perhaps main purpose of *sounds of hesitation* is to prevent the other party from grabbing the turn. This is functionality that we want to support in our dialogue game. For example, if our user is not interested in receiving intermediate results, yet knows he is not able to speak with a pace fast enough to avoid that, he might instead say:

\[
\begin{align*}
\text{U: } & 23+30\text{errrr}+312 \\
\text{S: } & 365
\end{align*}
\]

In other words, the user produces a sound of hesitation – transcribed here as “err” – in order to prevent the system from grabbing the turn and presenting the result of evaluating 23+30.

In general then, when a dialogue is in a state where a speaker induced pause *would* mean something, and what it *would* mean is not intended by that speaker, it is important for the speaker not to be silent and thus, as it were, ‘unintentionally’ produce a pause. We will assume that this is an important ‘rationale’ behind sounds of hesitation such as “err”. It is most likely not the whole story, but it is a mechanism that seems to do the job in our dialogue game.

### 2.3. Self-repair

The proposed dialogue game also supports a limited form of *self-repair*, i.e. the ability of the system to understand the speaker’s attempts to repair his own utterances, and to react properly. Consider the following example:

\[
\begin{align*}
\text{U: } & 2+2\text{no}3 \\
\text{S: } & 5
\end{align*}
\]

Indeed, in the proposed game, utterances of the expressions 2-\text{no}2+3, 2-\text{no}+3, 2-3\text{no}2+3, 2-3\text{no}+3 and 2-3\text{no}+3 all mean the same thing, and evaluate to the same answer, namely to the number 5.

Note that there is room for subtle forms of interaction between the processing of sounds of hesitations and the processing of self-repairs. Consider:

\[
\begin{align*}
\text{U: } & 12\text{errrrrrrr}03 \\
\text{S: } & 4
\end{align*}
\]

What happens here is that when the user has uttered [tu:], he immediately realizes that this is not what he intended. However, as he is not yet certain about what to say instead, he produces – while thinking – a sound of hesitation. He thus prevents the system from taking the turn and answer the question not intended (something that would make subsequent straightforward self-repair impossible). Had the user been silent instead of generating this sound, the dialogue might have ended up in the following confused and clearly undesirable state:

\[
\begin{align*}
\text{U: } & 12 \text{ no}3 \\
\text{S: } & 3
\end{align*}
\]

This concludes the description of our dialogue game design. We have not said anything about openings and closings of dialogues. In a realistic application, such things would also be important, but will be ignored here.

### 3. The Alice demonstrator

A demonstrator and research tool has been implemented – nicknamed Alice – which allows a user to enter into conversations of the kind described above. The processing architecture of Alice is based on the notion of *concurrent stream processing*. A *stream* is an ordered, open-ended and potentially unbounded sequence of tokens. Stream processors are *transducers* that transform input streams into output streams. The following code, written in the Oz programming language [4], forms the top-level of the Alice system.

```oz
thread {Listen S0} end
thread {FilterSoH S0 S1} end
thread {Repair S1 S2} end
thread {Chunk1 S2 S3} end
thread {Chunk2 S3 S4} end
thread {TakeTurn S4 S} end
thread {Speak S} end
```

Here, *FilterSoH*, *Repair*, *Chunk1*, *Chunk2*, and *TakeTurn* are transducers, composed so that *FilterSoH* reads the stream *S0* produced by *Listen* and creates another stream *S1* which is read by *Repair*, and so on. The resulting stream *S* is eventually spoken by *Speak*. As a clear proof of modularity we note that this is the only point in the system where the modules communicate.

The transducers are run in parallel – each in its own thread. It means that the system is able to listen, speak, and ‘think’ – e.g. perform all the important language processing steps in between listening and speaking – at the same time (although it doesn’t mean that it always does).

The threads are so called *dataflow threads*, i.e. they suspend on the availability of data [5]. Given two transducers running in separate threads, the second one will suspend if and only if it needs some part of the output stream of the first which is not yet available. An interesting and extremely useful consequence of this setup is full incrementality: if input is given incrementally, then the output will be computed incrementally as well.

A comparison with ordinary (finite-state) transducers may be useful. Ordinary transducers transform predetermined input strings into output strings, shutting out the world during the process of computation. Our concurrent stream transducers are transducers of incrementally generated streams, which means that interaction with the external world during computation is possible. This, of course, is crucial when processing dialogue.

The Alice GUI contains two ‘musical score notation’ fields. The user inputs his contributions in the field marked “U:” and – while the user types – the system responds in the field marked “S:”.

![Figure 1: The Alice demonstrator GUI.](image-url)
It is up to the user to indicate the passing of time by padding with space characters in the “U:” field as he sees fit.

By means of the Oz Browser the user is able to inspect the streams as they grow – a convenient feature when debugging.

Everything the user writes in the “U:” field is tokenized in an incremental fashion and each token is put in a stream. For example, if the user writes

3errrrr+14

the stream will look as follows:

\[ n(3) | e|x|r|x|r|o|p(+) | n(14) | s|_ \]

The system is not yet able to take spoken input or produce spoken output, but this is planned for the future.

### 3.1. Processing sounds of hesitation

As noted in Section 2.2, the purpose of sounds of hesitation is to prevent the other party from grabbing the turn. We suggest that by just being uttered, they have already served their purpose, because it means that – by necessity – pragmatically significant pauses not intended by the speaker have not occurred, and this is all that is needed. Consequently, the proper way to deal with sounds of hesitation in the system is to treat them as noise and to remove them – to filter them out so as to stop them from reaching deeper into the cascade of transducers.

What this means in practice is that a stream such as

\[ n(3) | e|x|r|x|r|o|p(+) | n(4) | s|_ \]

is simply transduced into

\[ n(3) | o|p(+) | n(4) | s|_ \]

### 3.2. A rewrite model of self-repair

In Alice, the transduction relevant to self-repair is implemented as a sequence of rewrite rules, a selection of which is shown here:

\[
\begin{align*}
\text{n(3)} & \rightarrow \text{no|n(N)} \\
\text{n(1)} & \rightarrow \text{n(N)} \\
\text{n(3)} & \rightarrow \text{n(4)} \\
\text{n(3)} & \rightarrow \text{op(+) | n(4) | s|_} \\
\text{n(3)} & \rightarrow \text{o|p(+) | n(4) | s|_} \\
\end{align*}
\]

A stream such as

\[ n(3) | o|p(-) | n(3) | o|p(+) | n(4) | s|_ \]

gets transduced into

\[ n(3) | o|p(+) | n(4) | s|_ \]

### 3.3. Parsing as two levels of chunking

In this section we consider the parsing problem as it manifests itself in our dialogue game. We want our parsing strategy to be incremental, and we want to resolve potential ambiguity in an intuitive way. Let us begin by reviewing our options.

With a mindset tuned to the parsing of written arithmetic expressions – and as victims of the “written language bias” in linguistics [3] – we might consider using a grammar such as

\[
E \rightarrow E+E | E-E | E*E | E/E | N
\]

to parse our arithmetic expressions.

However, it is easy to see that this is a bad idea. This grammar is highly ambiguous, and will produce numerous parse trees for moderately complex expressions.2 There are two standard ways to avoid this ambiguity problem. One is to introduce parentheses into the language and have strict rules for writing arithmetic expressions ensuring that there are always a sufficient number of parentheses to determine the order of operations. The other is to have precedence rules which tell us how to evaluate an expression (e.g. multiplication and division are performed before addition and subtraction). These strategies can be – and often are – combined, e.g. in the form of a grammar such as

\[
E \rightarrow E+E | E-E | E*E | E/E | (E) | N
\]

We will use neither strategy. The user should not have to ‘speak’ parentheses, and the use of precedence rules alone is not flexible enough. The solution here is basically to throw away everything we have learned about parsing of written arithmetic expressions. We will suggest a very simple chunking approach instead, part of which can be paraphrased as follows: “Once you detect a short pause in the input stream of sounds, go ahead and evaluate the chunk that you have heard so far. Remember the result, because the user may soon want to be presented with it, and/or it may serve as an operand in a larger expression of which you have so far only heard a part.”

It turns out that two levels of chunking, implemented by composing two simple stream transducers, are sufficient.

Figure 2 depicts the first transducer in the cascade.

![Figure 2: Level one chunker.](image)

This transducer has three states. Each state has a dynamically changing value associated with it, either a number or a unary function from numbers into numbers.3 The transducer also has transitions, each of which is labeled with two pairs of the form

\[ \text{In:Out} \] 

where In and Out are tokens and \( V_1 \) and \( V_2 \) denote the value of the leaving state and the arriving state, respectively. (Initially, the value of the start state (0) is the identity function.) The pair In:Out will map the token In in the input stream to Out in the output stream. In case Out is 0, In maps to nothing.

Processing works as follows. The transducer takes a stream of tokens as input, reads the stream one token at a time from

\[ 3 \]

---

2 In fact, they are known to have a combinatorial (Catalan) number of syntactic parses. E.g. 2+3*2+2*6+4 has 42 parses.

3 The lambda abstraction operator (e.g. \( n^n \) is the identity function), and \( \lambda (n) \) applies a function \( \lambda \) to an argument \( n \).
left to right, and writes corresponding tokens to an output stream.

![Figure 3: Level two chunker.](image)

The result of running this transduction on the input stream

\[ n(2) | op(+)| n(3) | s | op(*) | n(2) | s | s | _ \]

is the output stream

\[ n(5) | s | op(*) | n(2) | s | s | _ \]

This implements the first level of chunking. The result of running the transducer depicted in Figure 3 on this output is the following stream:

\[ n(5) | s | n(10) | s | s | _ \]

and this completes the parsing process.

### 3.4. Turn-taking

The turn-taking mechanism of our system is based on the transducer in Figure 4.

![Figure 4: Turn-taker.](image)

Given the stream

\[ n(5) | s | n(10) | s | s | _ \]

the turn-taking transducer produces

\[ n(10) | _ \]

and this is what is spoken to the user. Note that the intermediate result (5) does not pass through the filter and thus is not spoken. The pause is simply not long enough to allow the system to grab the turn.

### 4. Discussion

Although the full validity of our approach can only be determined once speech has been added to the system, we like to think of the work reported in this paper as a first attempt to build a truly asynchronous dialog system based on concurrent stream processing techniques.

Our dialogue domain of choice – numbers and arithmetic operations on numbers – is undoubtedly very simple, and it would of course be interesting to try to build dialogue systems over more complex domains using our approach. Even so, despite the fact that a lot of pragmatics phenomena (presuppositions, implicature, etc.) do not show in our dialogues, there is still room for a fair amount of variation, which we have yet to explore fully. For example, there are feedback moves [1] that would be natural to have in our dialogue game. Let us close this paper by looking at a few of those, commented very briefly.

User makes incomplete utterance. System prompts for completion:

U: 2+2+3                  
S:               + what?   7

User does not hear, and therefore (twice) prompts for (rephrased) repetition:

U: 2+3 what? *2 what?     
S:     5       2+3=5    10       5*2=10

User's query is ambiguous. System enforces disambiguation:

U: 2+3*2                yes
S: 3 +3*2? 10

Presumably, these moves would lend themselves to straightforward implementations in our framework.

### 5. Acknowledgements

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### 6. References