telemedicine,
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adaptive ECG interpretation

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PACKETIZING OF NON-UNIFORM TELEMEDICAL DATA WITH USE OF NESTED REPORT STRUCTURES

This paper presents an effective solution of packetizing of non-uniform data for the purpose of reporting in telemedical surveillance systems with adaptive interpretation. Unlike the regular systems, where the data continuity is guaranteed by the common reporting interval and unified report content, the adaptive systems must implement a reservation procedure in order to proper data delivery, accordingly to sampling rates set individually for each of the diagnostic parameters.

This procedure combines the content of every packet with respect to changes in data flow from particular diagnostic data, caused by time-variable requirements for the update rate of their time series. Our approach postulates appending to the information structure of two auxiliary data attributes, the validity period and the priority. The proposed solution was implemented and tested in a prototype cardiology-oriented monitor using two alternative reporting modes following the monitoring requisites. In *immediate mode* diagnostic packets are transmitted immediately accordingly to the time requirements, what allows the telediagnostic system to respond in short time in case of emergency. In *delayed mode* the transmission is deferred until packets are entirely filled with valid data, what limits the usage of data carrier for long-time regular reporting.

1. NON-UNIFORM DATA AND ADAPTIVE PROCESSING

The irregular data in telemedical surveillance report are a consequence of adaptive interpretation recently proposed as a method for close following the patient's needs without increasing the computational power required in a wearable recorder [2,3]. Irregular reporting also enhances the data communication effectiveness and helps avoiding of unnecessary energy dissipation. Due to the changes in data flow from particular diagnostic data, caused by time-variable requirements for the update rate of their time series, this innovation implies problems with data uniformity that needs to be solved in order to guarantee the data continuity. The proposed solution is disclosed beneath.

The system considered as an example prototype is designed for cardiology-based surveillance of patients in motion and uses a star-shaped topology managed by the central server over the bi-directional digital data link [7,9,11,12,14,15]. The interpretation task is independent for each of the patients and shared between the remote recorder and a corresponding thread executed on the multitasking central server (Fig. 1). The interpretation of the recorded ECG signal and the adaptivity of diagnostic report content are subjects of multicriterial optimization performed by the server [4].

The interpretive software consists of four classes of procedures:

1. recorder-only procedures, e.g. interfaces and recorder resources management, ECG signal acquisition and buffering, signal quality assessment,
2. recorder defaults preloaded as dll's but removable, e.g. procedures for QRS detection, morphology classification, wave delineation, arrhythmia detection,
3. recorder optionals available for mobile platform as dll's, e.g. procedures for ST- and QT-segment analysis, HRV time domain analysis, pacemaker pulse detection,
4. server-only procedures (not available as mobile platform's machine code), e.g. HRV frequency domain analysis, VLP detection, HRT analysis and others.

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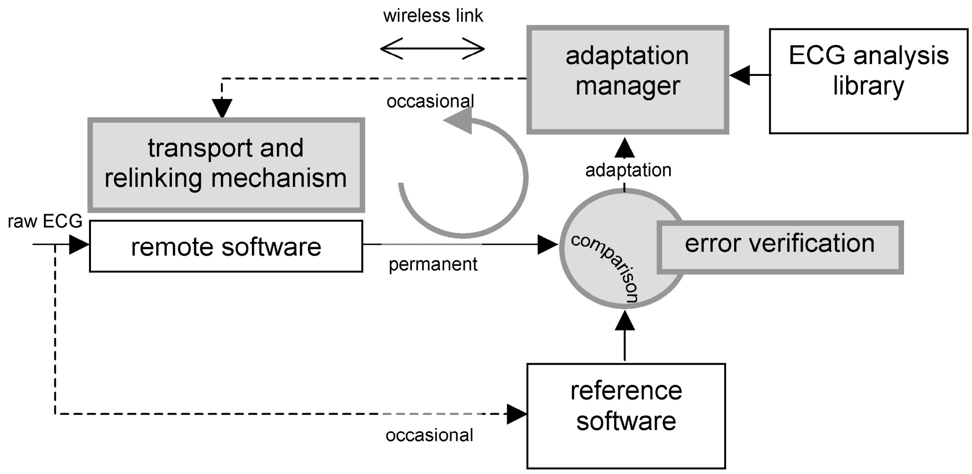

Fig. 1. Block diagram of the autoadaptive system for ubiquitous cardiology.

Multiple versions of 2nd and 3rd class procedures are compiled for both: recorder and server platforms. The adaptation of the remote interpretation process is achieved in real time with the use of diagnostically oriented libraries of subroutines. Subroutines within the libraries are commutable, thus designed for the same computational purpose, but with different prerequisites for the resources requirements and result quality. Their data gateways are standardized enabling the replacement required by the remote optimization, while the interpretation is running. Each subroutine is described by the attributes of quality, resources requirements and external dependency specifying its relations with the other components in the signal interpretation tree. Selected functions are uploaded from the repository managed by the supervising central server [1,16] and dynamically linked with the software running in the patient's recorder. The adaptation is performed automatically, but occasionally, in critical cases, it is supervised by a human expert connected through the central server. Switching between several variants of remote ECG interpretation implies respective adaptation of diagnostic report contents and consequently requires exceptional flexibility of the data transmission format. Testing the prototype of surveillance system with adaptive interpretation we had to face the problem of management of non-uniform multimodal data flow. The proposed approach minimizes data redundancy but respects individual update interval for each diagnostic parameter. It is based on dynamic definition of data structures and queuing of these structures in the output stream with respect to their values of update interval.

2. DATA CONTAINERS AND REPORT DESCRIPTION

2.1. LAYERED DATA FORMAT

As designed for the adaptive diagnostic system, the reporting format has to provide as much flexibility as possible. We implemented three-layer data format (Fig. 2) consisting of:

- mandatory header describing packets content and recorder's status,
- mandatory data description fields with pointers to the data,
- optional data fields or mandatory end-of-report mark.

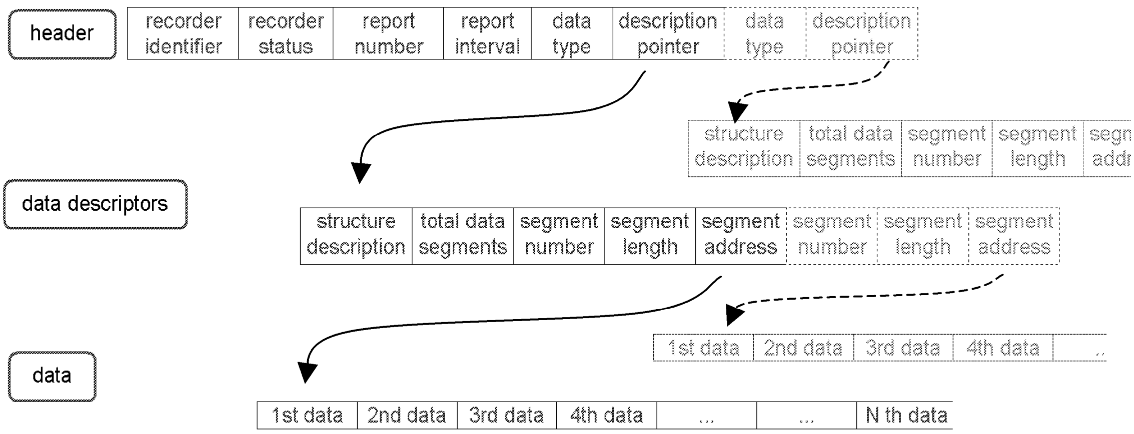

Fig. 2. Data communication format; mandatory fields are bordered by the solid line, optional fields are bordered by the dash line.

The header begins with unique identifier of the recording device (also identifying the patient) and the static structure of 18 bytes representing its status [2]. Following fields contain the session identifier, sequential packet number and the time interval to the subsequent report. Two later data are instrumental for the correct report queuing and for the server-side assessment of data integrity and continuity. Remaining header fields are used for description of the first data field type followed by the pointer to the first byte of its structure. First pair of such fields is mandatory even if the report is empty (i.e. contains only the end-of-report mark), but more often the descriptors of data fields with respective pointers are repeated within the header as many times as necessary to specify all used data types. This allows each report to be individually composed of any combination of predefined data structures. For the reason of multitude of data meanings (including raw signals, meta data, diagnostic parameters) and forms (simple variables, vectors, matrices and structures) used for the reporting, the description of data organization precedes the report contents.

In the data description layer, each data type specification is followed by at least one data allocation triplet consisting o the index, length and pointer to the particular record serialized in the data layer. In case of several consecutive records of the same type (e.g. a time series of values of a specific diagnostic parameter), all them are combined to a vector under a common data type definition.

The data layer consists uniquely of medical data serialized in their description order. First byte is addressed in the description layer by the pointer of the first segment of first data type defined in the header. In case of empty report this field contains the end-of-report mark.

Minimum length of the diagnostic report is 20 bytes, while the maximum length is unlimited and depends only on the transmitted data stream. In order to limit the contribution from TCP/IP overhead in transmitted data volume, reports below 256 bytes are sent only in immediate reporting mode. Reports exceeding 1500 bytes are split due to the limitation from the TCP/IP specification [8,10].

2.2. NESTED DATA STRUCTURES

The definition of data organization is a consequence and follows the confines of recorder software adaptation process. The software modification is prepared in advance and executed through switching between the precompiled alternative pieces of machine code in course of the patient monitoring. Similarly, the adaptive reporting procedure in the server prepares the communication at the beginning of each monitoring session in three steps:

- first examines the possible outputs of all considered interpretive procedures,
- builds an usage probability-ordered table of all available data structures and
- exchanges their description with the patient's recorder.

Up to 256 different data structures may be defined for each session, what was expected as sufficient for the necessary flexibility of the report content. Thanks to the primary definition, any particular structure is referred to in the report by a simple numerical identifier of size of a byte. Moreover, definitions of complex structures may embed the simpler, previously defined types.

This allows for definitions of nested data structures (Fig. 3) particularly efficient if two reported parameters are represented in time series having their update intervals of integer ratio. In this case a basic data aggregate is frequently included in the report, while the compound aggregate, including also the basic one is used instead in every n^{th} report. Although the minimum sampling frequency (or maximum update interval) is selected individually for each parameter with respect of the expected variability, rising the sampling rate of one of them to the nearest sub-multiple of the other helps to avoid alternate transmission of independent reports and saves the space under a common header of transmission protocol.

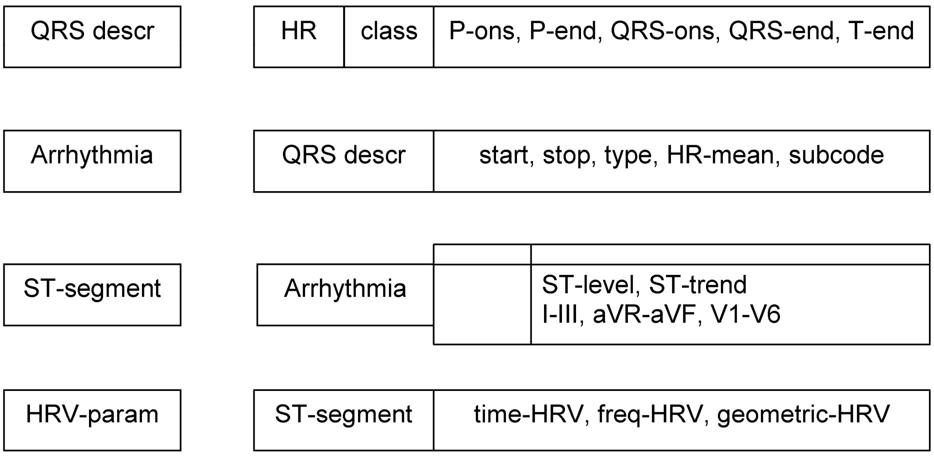

Fig. 3. Design of sample information structures for the adaptive reporting in the prototype of seamless cardiac supervising system.

2.3. SUPPLEMENTARY DATA ATTRIBUTES

The patient status and the monitoring goal determine the confines of record interpretation and the resulting parameters set. Since the variability of particular diagnostic parameters depends on their values (particularly between physiological and pathological), each diagnostic readout is attributed with supplementary descriptors. These are the *priority* and the *validity time*, the latter being the inverse of the minimum update rate required to maintain the continuity of each time series. Reporting each diagnostic parameter with its proper update rate optimally reduces the medical data stream. When aggregating the independent data into a hierarchical tree of nested structures the software examines their *validity time* attributes and decides to update all remaining values with a slight oversampling with respect to the update rate of the most varying parameter.

Each time, the interpretation software is modified, the report reservation procedure matches the attributes of diagnostic parameters with the information structures available for the session:

- parameters are roughly categorized by their temporal variability expressed by values of *validity time* attribute and each category is assigned by the structure best reflecting its content,
- a sequence of structures is defined and scheduled accordingly to the diagnostic parameter of shorter *validity time*.

The size of each category, measured as the difference of required update frequencies between its border members, is adjusted with regard to the volume of TCP/IP control data. The proposed data aggregation and scheduling rule guarantees the reporting continuity of each parameter and maintains the global data on its lowest possible volume.

In practical tests of the reports adaptivity, the number of necessary different data types rarely exceeded 16.

3. REVIEW OF REPORTING MODES

The prototype cardiology-oriented monitor was designed for a support of continuous long-time regular reporting with minimum data carrier usage, but was expected to respond in short time in case of emergency. To comply with these contradictory requirements it uses two complementary reporting modes the *delayed mode* and the *immediate mode*, with different approaches to data collection and packetizing.

3.1. DELAYED REPORTING

Working in *delayed reporting* mode, the recorder gathers the data accordingly to the required update rate, but allows for collecting the consecutive values in a single report in case the data volume is too low to fill the entire packet. This saves the protocol control data volume and the transmission energy at the price of delay in information delivery. This mode is defined for the routine monitoring of stable subjects. Due to data buffering, the transmission module may be temporarily switched to a low-power state in order to extend the recorder's autonomy time. The diagnostic representation of a remote patient is continuous, however due to the reception delay at the server, the last available data may not be recent. The *delayed reporting* doesn't require the continuous availability of wireless data carrier. Depending on the configuration, if the data carrier is available, the *delayed reporting* may be automatically switched to the *immediate reporting* mode in following cases:

- occurrence of pathological events,
- activation of the patient's button,
- adaptation of the remote recorder interpreting software,
- recovering from the carrier absence, if originally the *immediate reporting* mode was set.

In the prototype implementation, the *delayed reporting* mode buffers the subsequent diagnostic reports up to the size of 32kB or up to a delay of 360 s. If one of these limits is reached, the transmission module is activated and the packet containing several consecutive diagnostic reports is sent.

3.2. IMMEDIATE REPORTING

In the *immediate reporting* mode the recorder sends a report as soon as all included diagnostic parameters are calculated. This mode maintains both the continuity and minimum delay of the diagnostic patient's representation available at the server. This mode is particularly useful for the monitoring of high-risk patients, for synchronization of the patient-doctor interaction or for the immediate assessment of adaptation of the recorder's interpretation software. This mode requires the continuous operation of the transmission module and availability of wireless data carrier. Here again, the *immediate reporting* may be set as automatically switching to the *delayed reporting* mode in following cases:

- absence of wireless data carrier,
- recession of any condition imposing immediate reporting mode, if originally the *delayed mode* was set.

4. MANAGEMENT OF THE REPORTS CONTENT AND FREQUENCY

The adaptive nature of ECG interpreting software implemented in the remote (patient) recorder implies non-uniformity of the diagnostic report content. Moreover, depending on the patient's status, the *validity time* attributes is individually determined for each parameter by the management software in the central server. For those reasons, the management of the reports content and frequency is directly related to the adaptation of interpretive software in the patient's recorder.

The procedure managing of the data queuing in adaptive diagnostic reports is implemented in the remote recorder and thus - in spite of the importance of the performed optimization - should not require much of additional computation power. When the adaptation of the interpretation software is completed, the combination of diagnostic outcomes and their attributes (*priority* and *validity time*) has to be analyzed. As the result, most appropriate data structures and their repetition intervals are determined and used as components for building the report sequence. The sequence starts with the structure composed of all considered diagnostic parameters (ref. Fig. 4 point t_0) and then the subsequent structures and intervals are scheduled with regard to the required update interval. In case when several structures are applicable for a given parameters combination, the structure of minimum size is selected. When the use of the structure composed of all considered parameters is necessary again (point t_1), the queuing procedure assumes the report sequence is completed and contains the basic repetition period. The sequence is used for the reporting until the next adaptation of the recorder's interpretive software.

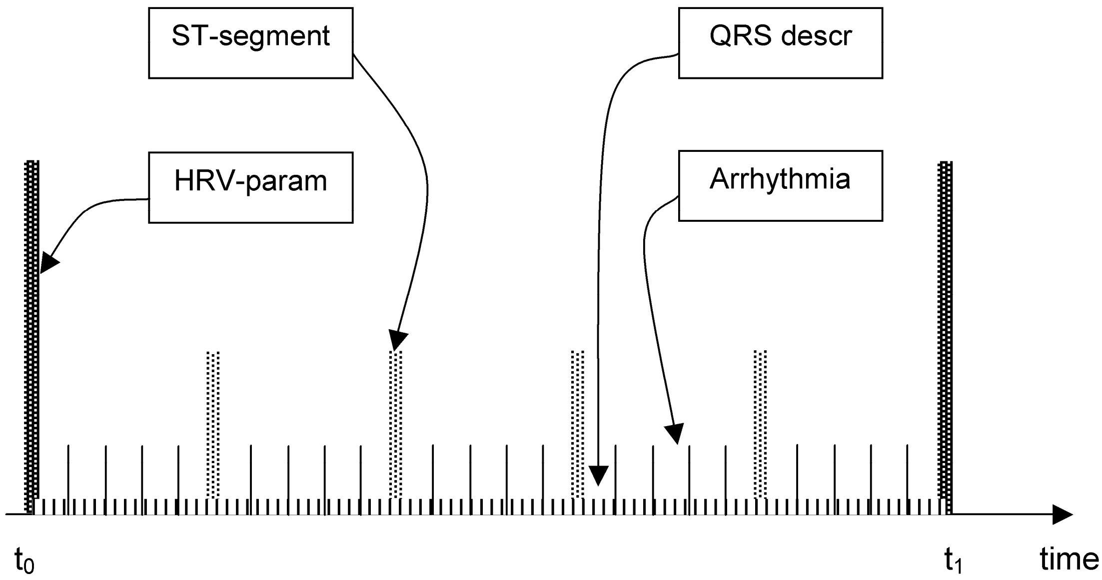

Fig. 4. Sample sequence of medical data structures used for reporting of the heart rate, arrhythmia events and level of ST section.

5. RESULTS

The prototype data queuing procedure was implemented in Matlab, before going further to the machine code of target operating system [18]. This implementation was aimed at testing the automatic building of report sequences for various combination of diagnostic parameters and their validity time and at verifying the benefits expected from non-uniform data queuing.

5.1. TESTING CONDITIONS

Four data structures were created as default for the transmission (see Fig. 3) and organized to a hierarchical tree in which each subsequent structure embeds the preceding one:

- heart beat descriptor *QRS Descr* (volume: 16 bytes, update interval: 300 ms),
- arrhythmia descriptor *Arrhythmia* (volume: 5 bytes, update interval: 3 s),
- ST-segment descriptor *ST-segment* (volume: 24 bytes, update interval: 30 s),
- HRV parameters descriptor *HRV-param* (volume: 10 bytes, update interval: 360 s)

Since the dynamic behavior of data queuing was the purpose of the test and in real patients cardiac changes are unexpected, we found reasonable to use 2751 signals artificially combined from 58 records of Common Standards for quantitative Electrocardiography (CSE) Multilead Database [17]. In each test signal the appearance of a single pathology was simulated by the concatenation of several repetitions of a record annotated as normal followed by several repetitions of a pathology-specific record. In the vicinity of the concatenation point, the count of samples was adjusted accordingly to the precedent RR interval and the baseline level of the subsequent record was corrected for each lead independently.

Such test records simulate the abrupt cardiac changes and facilitate the technical analysis of the adaptive system behavior.

For the reason of simplicity in our test we didn't concern the variations of patient status and its influence to the results. In a real application, however, various pathologies require specific diagnostic data set and assume individual variability of these data implying variations of update intervals.

5.2. TEST RESULTS

Main results presented in Table 1 show data volume values only for the reports composed of few basic diagnostic parameters and their most probable values of *validity time*.

Table 1. Comparison of the data stream volume [bps] using the constant reporting rate and the adaptive reporting with data queuing method proposed in this paper (12-lead ECG).

component	data volume [b]	validity time [s]	theoretical data stream	adaptive rate data stream	constant rate data stream
heart rate	1	0.3	55,277	65,67	181,5
morphology	1	0.3			
wave borders	14	0.3			
arrhythmia events	5	3			
ST-segment elevation	24	30			
HRV parameters	10	360			

In the *delayed reporting* mode, the size limit of 32 kB requires 580 s of recording. This value corresponding to maximum reporting delay of 9 min 40 seconds is high even for the stable subject. Consequently, we lowered the limit for data buffering interval to 360 s (6 minutes), what allows the buffer to accumulate nearly 20 kB of data. The wireless telecommunication module in a target hardware platform has to be operating (supply current 50 mA @ 5 V) for 6 seconds before the beginning of data transfer in order to re-establish the connection. The transfer session lasts for ca. 4 to 10 seconds depending on the speed of data transfer (16 to 40 kbps). Including additional 2 seconds for the session termination and disconnection, the module is operating for 18 s out of 360 s reporting interval. Since the energy consumption in standby mode is almost negligible (0.5 mA), the average energy in *delayed reporting* mode is reduced below 3 mA (i.e. to 6 % of the original value).

In the *immediate reporting* mode, the packet of minimum size (256 bytes) is collected within 4.63 seconds, which is slightly worse than the delay in the on-line interpretation process (typically 2 s), but still acceptable as real time monitoring. If the transmission in *immediate reporting* mode is used in a loop for modification of the interpretation process and verification of the outcome's quality, four iteration of software update are completed in 17.1 s.

6. DISCUSSION

The use of nested data structures arranged in a hierarchical tree and application of two supplementary attributes for management of data queuing was an effective solution for non-uniformly reporting from a patient's recorder in cardiac surveillance system. For each adaptively selected combination of diagnostic parameters requiring individually specified instantaneous update rate, the proposed automatic procedure schedules the sequence of data structure having minimum size and maintaining the data series continuity. The packetizing procedure is designed as a part of support for software adaptation process, but may also be used as a software interpretation trigger in asynchronous "on demand" interpretive systems, which are also sources of non-uniform diagnostic outcome [5, 6].

Regular ECG reporting implies a significant oversampling of certain parameters, and consequently - the waste of energy and telecommunication resources (Table 1). The intelligent data queuing uses several mutually dependent data structures and individual management of packet contents. Proposed method of aggregating diagnostic outcomes of different validity time is a compromise between following precisely the parameters' bandwidth variability at the cost of increase of the total volume of the transferred data and maintaining minimum data volume, which also reduces the energy consumption and transmission costs. Although some parameters are reported more frequently than it is necessary, but the oversampling synchronizing all parameters update is a source of still inferior data volume than contribution from the TCP/IP protocol control information.

The achieved result is satisfactory - the adaptive rate data stream (Table 1) measured during the experiment was reduced nearly to a third of constant rate data stream that would be necessary in case of rigid reporting format. Comparing to a theoretical data stream, our result is 18.8% worse. These additional data volume represents a collected result of oversampling for slow varying parameters and doesn't include the TCP/IP control headers. In our experiment we assume the constant bandwidth of particular diagnostic parameters and could strive for better approaching the theoretical data stream. In a real application, however, oversampling is difficult to control, because the instantaneous bandwidth varies with parameters' values representing the patient's status.

In general terms, optimization is based on a cost function identified in case of the diagnostic report with the volume of redundant data in a multidimensional discrete space with constrains. To maintain the continuity of data series, the corresponding value update interval cannot exceed the maximum *validity time* individually determined for each diagnostic parameter. Moreover, the usable volume of diagnostic report should be filled with valid data using at the same time minimum number of data structure definitions.

The proposed solution seems to be suitable also for other applications using distant reporting based on non-uniform signals. First hand examples come from other branches of telemedicine. This solution is thus a step towards the remotely personalized medicine. The newly proposed layered data format is based on a general definition and thus shows unprecedented flexibility. What is very important in the aspect of desired interoperability, it does not interfere with any existing data transfer standard (e.g. SCP-ECG [13]). Relying on flexible definitions, the proposed format extends the support of existing standards to non-uniform time series of diagnostic data, being a natural way of reporting from adaptive interpreting software.

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