1) Abstract

David is a bright, successful Michigan State University undergraduate student who is visually and motorically challenged. He uses a walker for assistance while traveling through campus. He recently fell down an unfamiliar flight of stairs on campus because he was not able to see the drop-off as he approached. He then used this experience as inspiration for the ECE 480 Capstone Team Four Smart Walker Device Project in order to find a solution. ECE 480 Capstone Team Four designed and built an intelligent sensor and feedback device to attach to David's walker. This device will alert David, allowing him to stop before pushing the walker forward into dangerous drop-offs. The Smart Walker Device consists of two sensors with microcontroller integration and a rechargeable power supply. Experiments were designed, with David's active participation, to determine the amount of time and distance needed to stop safely. Team Four also worked with David to test and implement the form of feedback he prefers for being warned of oncoming drop-offs. David and others with mobility and/or visual disabilities will benefit from the Smart Walker Device through increased confidence, safety, and independence.

2) Description of Clinical Need

The inspiration for this project came in as a request from a gentleman named David Shachar-Hill. David is a fellow Spartan student majoring in Interdisciplinary Social Science who suffers from vision loss and uses a walker as a mobility aid. Below is David's account of an accident he experienced that inspired the idea of the Smart Walker.

"I am a MSU student associated with the RCPD. I have significant visual and mobility disabilities, plus a moderate hearing loss in the high frequencies. I use a walker on campus, primarily for safety. Last year, I was walking in Brody Hall in a part of the building that I was unfamiliar with. As I was walking forward with my walker, I didn't see a flight of four stairs in front of me. As I approached the first stair, the wheels of my walker lurched forward, pulling me down the stairs with it. I was glad this wasn't a full set of stairs, but it was in fact quite a warning sign. Unexpected drop-offs and/or changes in the terrain pose the biggest hindrance to my independence and accessibility throughout campus and the community. My rehab doctor wondered if a simple "Roomba" knows not to go over an edge, why can't my walker? If there was a device that I could attach to my walker to warn me of changes in the terrain, I would have avoided the previously described accident. Anyone with mobility and/or visual disabilities could benefit from such an innovation tremendously, increasing confidence, safety and independence." -David

David turned his insight into an opportunity to solve the problem. He commenced work with The Resource Center for Persons with Disabilities (RCPD) at Michigan State University to develop an RCPD-sponsored project for submission to the Electrical and Computer Engineering (ECE) Department course ECE 480: Senior Capstone Design. ECE 480 is a rigorous 4-credit (3 is standard) design experience in which five-person student teams work with a Faculty Facilitator to make a viable contribution to an authentic problem submitted by a Sponsor. In Spring 2015, Smart Walker Device was presented as an official ECE 480: Senior Capstone Design project. Student Team Four, consisting of Trevor Dirheimer, Jeffrey Hancock, Dominic Hill, Yakov Kochubievsky and Sean Stewart Moore, along with their Faculty Facilitator Professor Virginia Ayres, accepted the challenge to create the first Smart Walker Device, an intelligent sensor and feedback device to attach to David's walker. Stephen Blosser, Assistive Technology Specialist for RCPD joined David himself as the project Sponsor and Customer, respectively. Susan Langendonk, Orientation & Mobility Specialist and currently Chair of the AER Orientation & Mobility Division, undertook to provide professional level guidance and evaluation for David when using the prototype Smart Walker Device.

Careful review of currently available state of the art technology by Team Four, and also by Stephen Blosser and Susan Langendonk, indicates that there is no device currently on the walker market that can detect changes in elevation from a safe distance. This is also true for four-point canes and wheelchairs. From the field of intelligent wheelchair research, Stephen Hayashi described the problem: "There have been several different implementations of 'intelligent' wheelchairs, which are able to detect obstacles in the environment and assist with navigation and obstacle avoidance. These wheelchairs are intended to aid wheelchair users who have difficulty driving a standard wheelchair due to visual impairments, fine motor limitations, cognitive challenges, and other impairments. These devices have focused on detecting upright obstacles, such as walls, furniture, and people. Unfortunately, many of them do not implement any way of detecting drop-offs such as curbs or descending staircases. Such drop-offs can pose a more serious risk of injury than upright obstacles" [1].

Research and development by Michigan State University Team Four identified and resolved key fundamental and system integration challenges in order to produce the first successful working Smart Walker Device prototype. Their original solution is based on LiDAR remote sensing technology with microcontroller intelligence integration with internal flash memory storage and power pack technology capable of > 24 h continuous operation. All of these technologies have just recently become available at acceptable costs. For example, several researchers pointed out in 2007 that the cost for laser sensing of drop offs would be too high for practical application [2]. By 2015, this assessment had radically changed and Michigan State University Team Four was quick to take advantage of it. The cost of the Smart Walker Device prototype including all materials, electronics, LiDARs, microcontroller with flash memory storage, and power supply was $582.73. An estimate based on bulk purchase prices for the same parts indicated that the cost per unit could be immediately lowered to $314.36.

The design and methods used to create the Smart Walker Device will be a breakthrough for the medical device industry, as well as for any user with disabilities of this nature. The success of this design will prove to be versatile as it can also be used by users with visual and motoric disabilities across multiple demographics including senior citizens, stroke patients with vision loss and/or balance impairment and veterans also with vision loss and/or balance impairment due to traumatic brain injuries. Quality of life for all users will improve by offering them a Smart Walker Device device that will ensure their safety, as well as offering them further confidence and personal independence.

3) Design and Innovation

A key challenge for drop-off versus obstacle detection is shown in Figure 1. Horizontal obstacle detection (black arrows) takes place at near normal incidence with several transceiver (signal/sensor unit) types capable of providing detection with sufficient stopping distance. Vertical sensing at near normal incidence is also readily achievable but the stopping distance is unacceptably short (blue arrows). Drop-off detection involves sensing the return signal at an angle set by the patient's safe stopping distance, which will be several stride-lengths in front of the walker (red arrows). This is far from normal incidence with much of the signal reflected forward. Only part of the original signal scattered backward by surface irregularities will be received at the walker. Beam width is also a critical concept in distance sensing. Beam width is determined by the angle of beam divergence from the source and the distance to the object being measured. A very broad beam width results in undesired objects being detected by the sensor while a very narrow beam width might not detect a drop-off if a walker isn't aimed directly at the drop-off. Furthermore, a wider beam divergence contributes to a weaker returned signal.

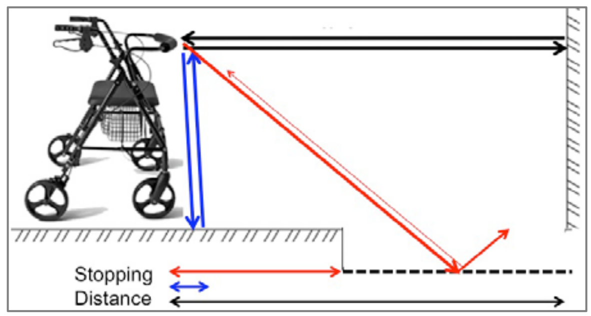

Figure 1. Safe drop-off detection introduces the need for angular detection.

Team Four first determined the ideal criteria to determine a drop-off. As shown in Figure 2, these are:

- The distance measured from the sensors to the target (length A in Figure 2) **increases** by length dh
- The distance measured is **larger** than length A. This ensures that a person walking in the measuring path of the sensors doesn't trigger the alert.

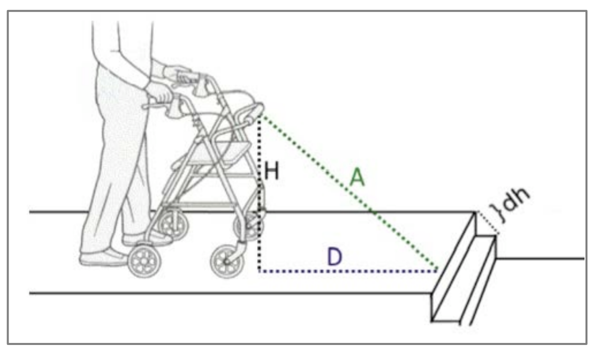

Figure 2. The sensors constantly sample the distance A, then A +dh. Length H is the top crossbar height of the patient's walker. Length D is the patient's safe stopping distance. For David, these are: H = 2.5' and D= 4.0'.

The Smart Walker concept had already been clearly defined by David. However the more specific voice of customer had to be identified, including critical customer requirements, to enable creation of the actual device. The highest priority customer requirement was to issue a warning for David that provided ample time to stop before a dangerous drop-off. This meant that a distance needed to be determined between the position that David is alerted, to the position that David comes to a stop. Team Four developed the following simple, portable test to determine David's stopping distance: a measuring tape was placed on the floor with a strip of black tape placed at every foot marker. David was then instructed to move at a hurried pace while a team member triggered the audible alert at a position unknown to David. As soon as David heard the alert, he was instructed to stop his walker. Consistent results for a healthy, young and motivated subject were obtained after 10 experimental trials. Team Four concluded David's safe stopping distance to be 3'6", determined by the longest distance registered during the experiments to get a worst-case scenario. 4'0" was therefore the warning distance that Team Four decided to implement, adding 6" to the stopping distance to ensure that David had ample time to stop. Once the highest priority customer requirement, a safe warning distance, was identified, additional critical customer requirements were investigated, using a Design for Six Sigma process. These were found to be: transferability to different walkers, all-weather robustness, battery life of at least one day, lightweight device, mechanical robustness to vibrations during all use conditions, low cost, and low power consumption.

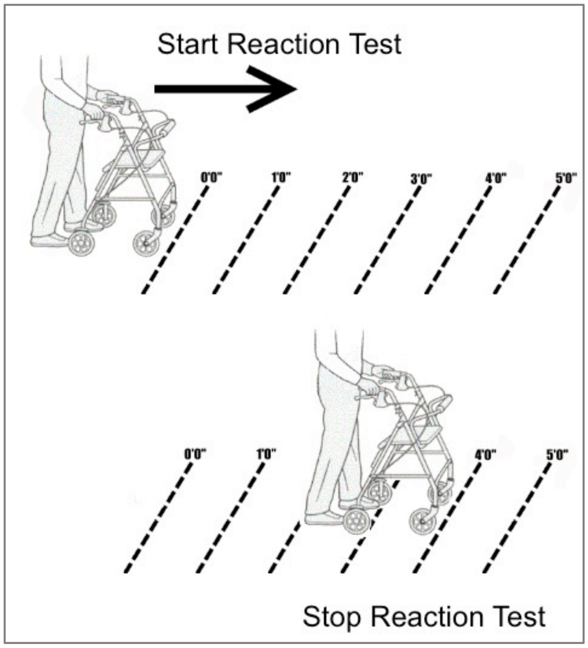

Figure 4. A simple, portable test was developed to determine the patient's safe stopping distance.

Numerous engineering methods can be used to achieve these deliverables. A Feasibility Matrix For Solution was created to narrow the choices and pinpoint the most effective design. The primary areas of implementation consideration were sensor type, microcontroller configuration, and the type of housing. Some details are given here because the Feasibility Matrix process, when performed for a future statistical sampling of users, can yield quantitative insights into Smart Walker Device for specific demographics.

Different combinations of design features were arranged into five design methods and assigned a feasibility score for each design requirement, with the design method with the highest score tally to be selected. Design *criteria* are assigned a level of importance to the patient (5 being the highest and 1 being the lowest). Design *solutions* are assigned a level of strength by the bioengineer that corresponds to how well a specific solution meets the specific criteria (9 being the strongest and 1 being the weakest). *Solution strength* is the product of design criteria and solution. Solution strength is summed in order to give each solution a *value*. The Smart Walker Device criterion that received David's rating of most importance: 5, was the ability to alert the user at least 4 feet ahead of a drop off. The battery life received a rating of 4, as running out of power would render this product useless; and the ability to withstand moderate impact also rated 4. The ability to work outside, being transferrable to different walkers, durability, and avoidance to sensitivity to different surfaces rated 3, as functions that increased the usefulness of this product, but were not critical to the core functionality. Aesthetics, while important for future marketing purposes, received a rating of 2 because safety is a direct result of the functionality for this product, not aesthetics. The solution ultimately identified by its highest value was: (2 LD, 1: 32 kB, 1: Al), which is: 2 laser diode (LiDAR) sensors, 1 microcontroller with 32 KB RAM and 1 strong lightweight Aluminum housing/harness. All design solutions were initially ranked, investigated and re-ranked. These included combinations with ultrasonic sensors, infrared sensors and a 3D printed case housing/harness. The Feasibility Matrix is a living document that records up-to-date system integration test results and prototype testing results.

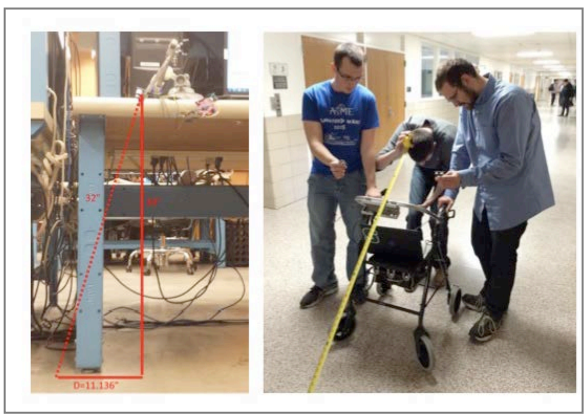
Figure 3. Angle of depression tests for all candidate sensor types proved critical to success. Shown: D. Hill, S. Moore and Y. Kochubievsky.

Iterative research and development by Team Four identified and resolved several key system integration challenges in order to produce the first successful working Smart Walker Device prototype. Team Four determined that angle of depression plus wider beam divergence for ultrasonic sensors (1) HCSR04 and (2) enhanced PING))) Ultrasonic Distance Sensors resulted in failure to read past *best* performance stopping distances D equal to 2'0" and 3'5" respectively – seriously less than David's safe stopping distance. The ultrasonic sensor failures were not predicted based on their specifications, but that they did so was a reminder that specifications are coupled to testing environment, in this case, normal incidence. The Team Four tests had never been performed at the factory.

More powerful and narrower divergence infrared sensors were next investigated but failed due to wide variations in performance caused by differences in absorptivity on differently colored surfaces. The sensor challenge was overcome with the selection of LiDAR Lite Laser sensors for the final successful prototype. These were provided to Team Four at a discounted rate by Pulsed Light 3D from the interest that developed after telephone discussions of the project's goals and challenges. Their accuracy and success at detecting elevation changes at David's 4' safe stopping distance was consistently more than sufficient. Laser-based LiDAR sensors have a minimal beam divergence of 0.5^{o}. However, Team Four determined that a design using two LiDAR sensors positioned on opposite sides of the top crossbar centerline at an easily packaged 6" separation enables accurate drop-off detection when approaching hazards at an angle.

Investigation by Team Four further disclosed that the sensor-microcontroller combination is almost unique for each sensor type. The successful Pulsed Light 3D LiDAR Lite Laser sensors are geared to the Arduino family of microcontrollers. Deciding which microcontroller to use is a critical decision. Since the microcontroller is constantly reading and writing data, it needs to be equipped with sufficient RAM to handle storage of multiple data points. Furthermore, it is also necessary to have a microcontroller that has built in Analog-to-Digital converters (ADC) for its I/0 channels. The sensors will be sending data through an analog signal; of which, cannot be computed in the Central Processing Unit (CPU) until the signal is converted digitally. It must be algorithmically capable of accurate distance comparisons based on sensor input plus triggering and control of an alarm circuit. Due to slow speed of the user's movement with his/her walker, the required sampling rate is relatively low and not an issue for any modern microcontroller. The Arduino Nano (ATmega328) microcontroller was selected for system integration. Its hardware and software capability proved to be excellent fit for the Smart Walker Device operational needs but its near mandatory use for Pulsed Light 3D LiDAR Lite Laser sensor implementations should be born in mind.

During meetings with David and the RCPD Sponsors, David earnestly expressed his conviction that an auditory warning system would be the best form of feedback to alert him to a sudden drop-off. The RCPD specialists, who are familiar both with David and with best practices for patients who are visually and motorically challenged, corroborated this. Team Four therefore developed a feedback system that produces an audible warning when triggered by detection of a drop-off. Two options for the feedback system were investigated. The first consisted of using the capabilities of the Arduino Nano, which has a Tone library. This was tested and successfully triggered when a drop-off was detected. However, the available quiet tone volumes of 0 to -15 decibels (dB) would be hard to hear in any public area with street traffic, foot traffic and human conversation (~ 60 dB). It was concluded to be too quiet even though it was the simplest implementation. RCPD Sponsor Stephen Blosser suggested an auditory feedback system that he designed for a different application ("Beep Baseball"). This system consists of two piezo speakers connected to a pre-fabricated sound generator circuit and produces a satisfactory ~80 dB warning beep. Team Four designed and implemented a substantial adaptation of the Beep Baseball circuit for use with the Smart Walker Device.

Other forms of feedback, in addition to auditory, will be desired for future Smart Walker Device implementations. These can include visual and haptic feedback systems to alert the user with the following disabilities and limitations:

Deaf or Hearing Impaired User: For a user with hearing impairment(s), a visual warning would be the best way to gain the attention of the user. An LED warning light combination is the simplest solution due to its ease of integration and low cost. A selection of customer-specific cues can be designed and implemented.

Deaf or Hearing Impaired & Blind or Visually Impaired User: For a user with both hearing and visual impairment(s), a haptic form of feedback would be the best means of warning. Since the user is in constant contact with the handles of the walker, feedback routed through this area is the best solution. Small, lightweight piezoelectric motors are available that can be utilized to send vibrations throughout the handles of the walker to warn the user.

It is of the utmost importance that the Smart Walker Device system developed by Team Four can operate for the entirety of David's most demanding days. Anticipating a 12-hour day, all power calculations were done using 16 hours of continuous operation, which provided the Smart Walker Device with a 25% safety overhead. The continuous current draw of the primary components of the circuit and the calculated expected draw accounting for hours of operation were calculated assuming 16 hours of total operation over a given day except for the piezo speakers, which assumed one hour of total operation as their worst-case scenario. These calculations determined that 3543.12 mAh is expected draw at 5 V which gives a 17715.6 mWh power requirement in a given day. The Smart Walker Device prototype uses a Lithium ion battery to power the circuit so battery efficiency must be accounted for as well. The actual power draw can be found using the equation $W_{actual} = W_{calculated}/efficiency_{battery}$. The efficiency of a Lithium ion battery is approximately 80%, leading to W_{actual} = 22144.5 mWh or 22.15 Wh. After evaluating several power supply options, Team Four decided that the ANKER 2nd Gen Astro E4 13000mAh rechargable power bank, which has a 48.1 Wh capacity, exceeds the performance requirements and presents a cost effective solution. Our calculations indicate that the current draw from the two sensors, the feedback system with two piezo speakers, the microcontroller, and the PCA9544AD I2C multiplexer chip could be supplied by the ANKER power supply for up to two days.

To confirm that the ANKER power supply would be able to satisfy the power demand of the Smart Walker Device, Team Four developed a stationary in-lab test, in which the Smart Walker System was required to run for a 16-hour day. The walker was set up in the lab at 8:00 AM with a fully charged power supply that ran continuously until 12:00 AM. The microcontroller was reprogrammed to trigger the piezo speakers anytime the distance detected was changed. This was done in order to keep the Smart Walker in one location while testing the battery life so that an actual drop-off was not needed for testing. Members of the Team would come in through the day to trigger the alarm. By the end of the test period, the alarm was triggered 50 times. The test experimentally confirmed that the Anker power supply was sufficient to power the device for a 16-hour day including drop-off detection well in excess of anticipated use. This test confirmed the predictions that the 13000 mAh power supply would see David safely through a full day of Smart Walker Device usage.

Figure 5. (a) Power supply housing, (b) battery life indicator, and (c) ANKER power supply in housing. (d) Fabricated crossbar and housing, and (e) Team Four final prototype.

Housing. Team Four designed a lightweight protective metal case/harness to house the power supply in on the side of the walker (Figure 5 (a)). A slot provides a clear view of the battery life indicator to the user (Figure 5 (b)). The Anker power supply is charged via a micro USB port that is easily accessible from the unit housing to allow for overnight charging (Figure 5 (c)). The LiDAR sensors, microcontroller, and the auditory feedback alert circuit are enclosed in a second compact aluminum case/harness attached to a fabricated top crossbar on the walker (Figure 5 (d)). An LED and switch are incorporated into the backside of the device housing to provide a simple and user-friendly way of turning the Smart Walker Device on and off. The switch controls circuit completion from the power supply to the 5V pin on the microcontroller, the sound generator circuit, the two LiDAR sensors, and the PCA9544AD multiplexer chip. When the switch is on, the circuit is complete and provides power to the bus line that provides the power to the device. The Team Four Smart Walker Device prototype as delivered to David is shown in Figure 5 (e).

4) Documentation of Successful Prototype

Video. The video submitted with this application [3] documents the creation of the successful Smart Walker Device prototype. In our video, David uses his new, intelligent walker to navigate in an unfamiliar public hotel setting. Inside the hotel, David uses the Smart Walker Device prototype to stay safely away from a set of stairs and, not shown, a nearby escalator. Outdoors, David uses the Smart Walker Device to stop safely when exiting a curved ramp with a nearby curb. The warning beep is clearly audible over both ordinary street noises and the louder competition furnished by a nearby commercial lawnmower. David discuses what his new freedom means to him and Susan Langendonk discusses what this can mean for many potential users.

Thresholds. We conclude with a brief discussion of the threshold conditions set for our initial ("factory") calibration of the Smart Walker Device prototype. Explicit thresholds must be programmed into the microcontroller in order to trigger the drop-off detection feedback system. To warn the user of an approaching drop-off, two thresholds needed to be determined. The first threshold is the drop-off threshold, which is the distance value that old and new distance values can vary by so that the warning beep triggers for stairs and other drop-offs but not for variations of few hundredths of a foot on what is essentially a level walking surface. The second threshold is a minimum height threshold, which is the direct line of sight threshold distance from the surface to the sensors. Establishment of the minimum height threshold prevents false triggering when a rapidly changed reading occurs within a short distance, e.g., when someone walks past a walker equipped with a Smart Walker Device. With the basic threshold considerations now established from our initial tests described below, an auto-calibration procedure can follow.

Team Four determined the drop-off threshold by conducting multiple tests with the prototype. Team Four first tested the change in distance in a universal stair scenario (8.25" step height, 34^{o} pitch, 9" tread). As the Smart Walker Device prototype approached the stairwell, it had a distance reading of 6.20'. When the device detected the drop-off in the stairway, the distance reading increased to 12.57', which indicated that the LiDAR sensors detected the distance to the bottom of the stairwell. Team Four concluded that, while the change of distance readings would vary with stairwell depth, drop-off detection in any multi-step scenario is unlikely to pose a problem. Team Four then considered possible one-step drop-off scenarios and conducted tests at sites found on the Michigan State University campus; it was interesting to "map" the campus in terms of its stairs. Team Four located and conducted tests for 8.0", 6.5" and 4.5" one step drop-offs, and obtained average change in distance readings of 1', 8.5" and 6.5", along with consistent triggering of the warning beep. From these tests, a safe drop-off threshold of 6.0" was established and programmed.

Figure 6. David and Team Four tested the Smart Walker Device prototype in multiple campus locations. These stairs are outside the RCPD entrance.

After Team Four determined the drop-off threshold, the testing for the minimum height threshold began. Team Four determined this threshold by first investigating line-of-sight distance readings for 14 different indoor/outdoor surface types. This test demonstrated almost 4" of difference in distance readings between light-colored, hard, glossy surfaces and dark, shaggy carpet surfaces. The Smart Walker Device prototype was then tested on a ramp. A loading ramp with a 14.5^{o} declination was used for this test, representing a need-to-know situation instead of a 4.8^{o} declination public access wheelchair ramp. When the Smart Walker Device prototype sensed level ground, its average distance reading came to 6.24'. When the walker reached the top of the ramp with all wheels on level ground, the distance reading was 6.71'. As the walker rolled down the declination plane, its distance reading was again 6.22' feet again. After conducting both tests, Team Four established and programmed the minimum height threshold as 6.8'.

Figure 7. left to right: Yakov Kochubievsky, Sean Moore, David Shachar-Hill, Trevor Dirheimer, Stephen Blosser and Dominic Hill. Jeffery Hancock, cameraman.

Summary. Team Four had many challenges to overcome with this project. The most significant challenge was finding the best sensor to meet the stopping distance requirement and keep David safe from dangerous drop-offs. Team Four overcame this and other challenges through innovative design, research, testing, and re-design phases, plus teamwork. As a result, Team Four has created a successful Smart Walker Device prototype that is delivered to David, who is ecstatic with this extension of his ambulatory capability. Team Four is proud and humble to realize that the Smart Walker Device now provides the awareness that David needs for drop-off safety, as well as the potential that our design has to help many others who use walkers and need an extra aid.

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